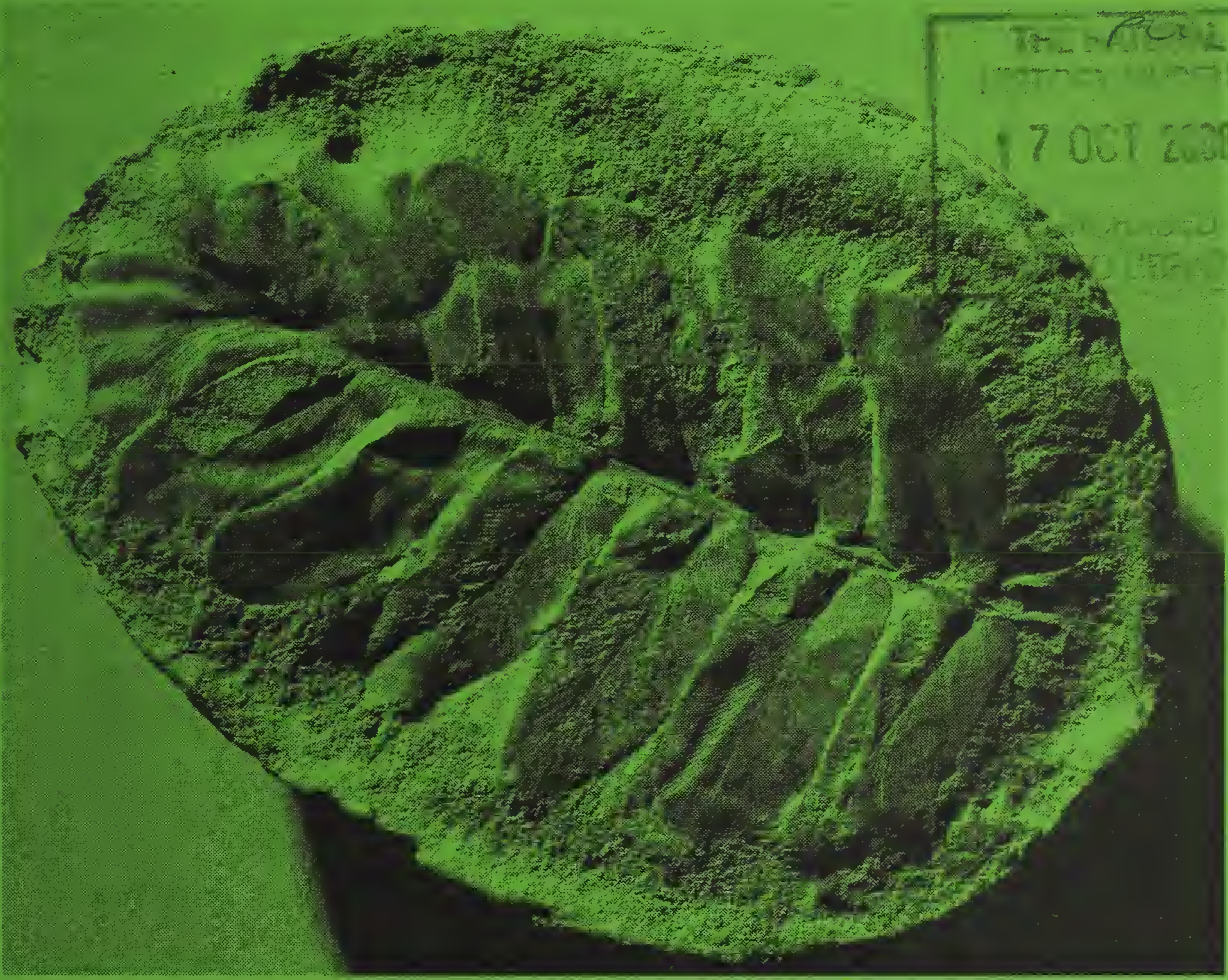
PS. 146

BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

NO. 58 2008

THE NATURAL
HISTORY MUSEUM
17 OCT 2008
PURCHASED
LIBRARY



CONTENTS INCLUDE

Tectonics, surface uplift and river incision

Glacial erratic collection

Clay mineralogy of Cromer Forest-bed Formation

Natural History Museum Library
000228115

BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK
No. 58 (2008) Published 2008

Editor: Julian E. Andrews

School of Environmental Sciences,
University of East Anglia,
Norwich NR4 7TJ

Telephone 01603 592536
FAX 01603 591327
E-mail J.Andrews@uea.ac.uk

EDITORIAL

This Bulletin contains three quite different papers that touch upon topical issues in East Anglian geology. The first paper by Prof. Mike Leeder is a summary of his Presidential Address to the Society in April 2008. This paper takes a world view of tectonic uplift and its effect on river incision, but then focuses on late Quaternary regional-scale uplift in East Anglia, which it is proposed, was driven by erosion of the Wash-Fenland embayment during the Anglian glaciations. This is clearly an exciting hypothesis that deserves further research and quantification. The paper by Hoare and Larkin describes the archive collection of glacial erratics held by the Castle Museum in Norwich, which should prove to be an important resource for those interested in the provenance of East Anglian glacial events. The last paper by Brough and Andrews is a study of clay mineralogy in the clay- and silt-stones of the Cromer Forest-bed Formation sediments at West Runton, Norfolk. They conclude that most of the clay minerals derive from either crustal weathering or early diagenetic formation in marshy environments, down-playing earlier suggestions that smectitic clays were mainly volcanologically sourced.

INSTRUCTIONS TO AUTHORS

Contributors should submit manuscripts as word-processor hard copy. We accept typewritten copy and consider legible handwritten material for short articles only. When papers are accepted for publication we will request an electronic version. We can handle most word-processing formats although MS Word is preferred.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation etc. conforms as strictly as possible to that used in Vol. 53 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

Illustrations should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black or grey should be avoided as these can spread in printing. Original illustrations should, before reproduction, be not more than **175mm by 255mm**. Full use should be made of the first (horizontal) dimension which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half tone photographic plates are acceptable when their use is warranted by the subject matter, provided the originals exhibit good contrast.

The editors welcome original research papers, notes, comments, discussion, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

TECTONICS, SURFACE UPLIFT AND RIVER INCISION: GENERAL MODELS, CASE HISTORIES AND APPLICATIONS TO EAST ANGLIA AND SOUTHERN ENGLAND

M.R. Leeder

School of Environmental Sciences,
University of East Anglia, Norwich, NR4 7TJ, U.K.

ABSTRACT

Many rivers worldwide have incised into their own alluvial deposits or into bedrock during the Quaternary, some producing spectacular terrace flights as they have done so. Whilst some authors have assumed that tectonic uplift is responsible for incision it is emphasised here that incision has other general causes. In this contribution two causes are discussed that are relevant to incision into older alluvium: 1) non-uniform sediment transport rate according to the sediment continuity equation ***(SCE)****; 2) non-uniform transport according to the sediment diffusion equation* ***(SDE)****. The assumption that surface uplift is generally required for incision and terrace flight formation is thus rejected.* ***SCE*** *and* ***SDE*** *modes of incision are demonstrated and contrasted with reference to the Quaternary history of the Rio Grande, SW USA* ***(SCE*** *incision) and drainages traversing the southern uplifting flank of the Corinth rift, central Greece* ***(SDE*** *incision). In East Anglia, a phase of permanent surface uplift is postulated following severe (up to 100 m) erosion of western Mesozoic scarplands by the southward-flowing Anglian ice sheet that funnelled through the Wash gap between Lincolnshire and Norfolk during MIS 12, about 400 ka ago. This erosional episode, termed the Clayton Event after its first quantifier, was followed by regional uplift and eastward tilting of older (2–0.6 Ma) marine Norwich and Wroxham Crag deposits. The magnitude of uplift and tilting is shown to be commensurate with isostatic response to the Clayton Event: either by local Airy compensation or, more likely, by regional flexural deformation The hypothesis that Quaternary surface uplift and terrace formation over southern Britain and elsewhere are due to isostatic adjustment driven by lower crustal flow is rejected, both on general and particular grounds.*

Bull. geol. Soc. Norfolk (2008) **58**, 3–36. Presidential Address given to GSN AGM, April 22nd 2008

INTRODUCTION

In this contribution some simple models are described for landscape incision by river erosion. They are applied to the tectonically active Rio Grande rift, SW USA, and Gulf of Corinth Rift, central-southern Greece. Whilst both rifts are tectonically active and their drainages have suffered the vagaries of Quaternary climate change, only the latter is affected by sea level change. The SW USA and central-southern Greece case-histories enable a fresh look at Quaternary development of the East Anglian landscape, particularly for evidence of late-Pleistocene uplift, tilting and river development linked to Anglian ice sheet denudation of the western scarplands. Finally, some pitfalls are noted in published interpretations of the origins of river incision and terrace development by surface uplift in wider East Anglia, southern Britain and elsewhere.

The relief and elevation of the continental land surface is influenced by external drivers such as tectonics and by changes in climate, hydrology and base level. Tectonic subsidence creates potential space for sediment deposition whilst uplift produces the gradients necessary for erosion. Climate on the other hand provides the water needed for vegetation and soil development, the runoff that allows hillslope sediment transport and the eventual sediment and water flux into a river system. Climate change can alter the balance of a river's hydrological and sediment supply variables so that erosion is commonplace in the Quaternary and older sedimentary records of both tectonically stable and active areas (Blum & Tornqvist, 2000). Another reason for erosion and exposure is global or local sea level fall or lake drawdown (Posamentier & Vail, 1988). For example, coastal plain rivers may override subsidence by incising in response to lowered sea level across a gradient change at the coastal plain:shelf break (Posamentier & Vail, 1988; Leeder & Stewart, 1996; Swenson, 2005).

Tectonic, climatic and base level induced changes to the hydrological cycle in a catchment are dynamic, with potential, kinetic and thermodynamic energy transfers and transformations taking place constantly within the system (Kirkby, 1999; Kirkby *et al.*, 1998). Catchment processes create the entire basin landscape from a number of prior conditions, rather analogous to the *Nature v. Nurture* concept for individual human development, whereby genetic make-up (*nature-providing*) is acted upon by external circumstances (*nurture-modifying*). Tectonics and lithological make-up are the given catchment ′genes′ whilst hydrological variables nurture and modify the sediment transport process.

GENERAL MODELS FOR RIVER BEHAVIOUR

River equilibrium

A graded equilibrium river was elegantly defined by Leopold & Bull (1979) as "*...one in which, over a period of years, slope, velocity, depth, width, roughness, pattern, and channel morphology delicately and mutually adjust to provide the power and efficiency necessary to transport the load supplied from the drainage basin without aggradation or degradation of the channels*" (emphasis is mine). The definition is suitably broad and stresses the complex interactions between river variables that control equilibrium. It also emphasises the longer time scales, but perhaps not sufficiently, over which equilibrium must be assessed.

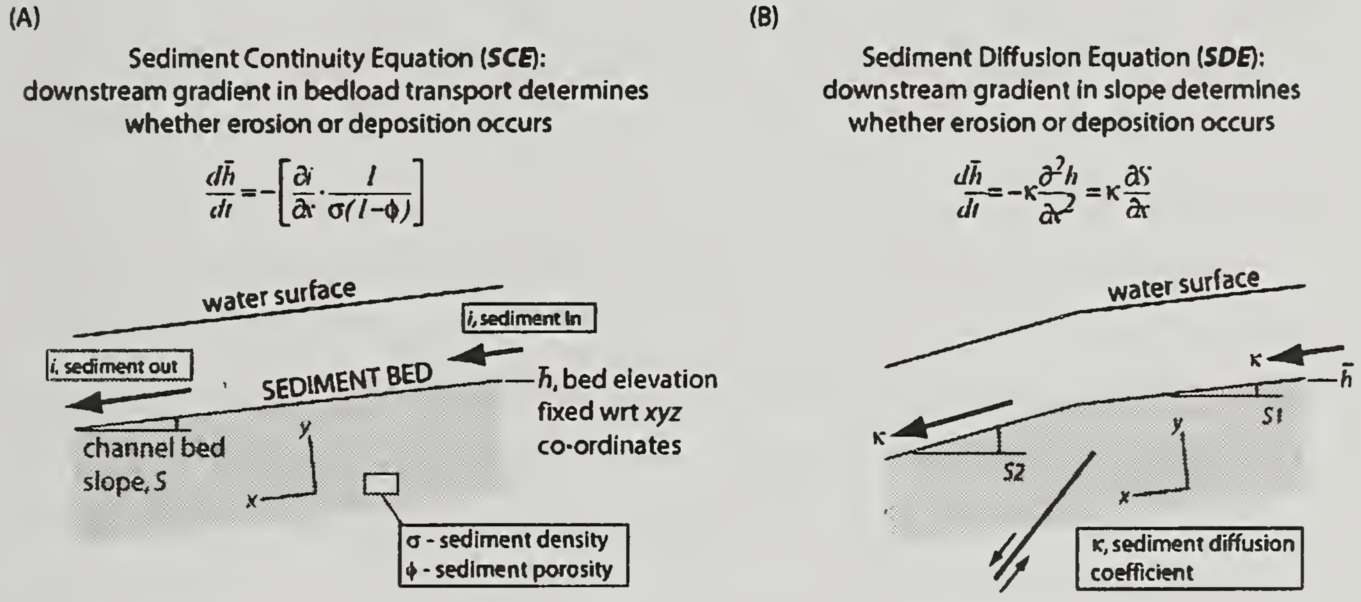

(A)
Sediment Continuity Equation (***SCE***):
downstream gradient in bedload transport determines
whether erosion or deposition occurs
$\frac{d\bar{h}}{dt} = -\left[\frac{\partial i}{\partial x} \cdot \frac{1}{\sigma(1-\phi)}\right]$
water surface
i, sediment in
i, sediment out
SEDIMENT BED
h̄, bed elevation fixed wrt xyz co-ordinates
channel bed slope, S
y
x
σ - sediment density
ϕ - sediment porosity
(B)
Sediment Diffusion Equation (***SDE***):
downstream gradient in slope determines
whether erosion or deposition occurs
$\frac{d\bar{h}}{dt} = -\kappa\frac{\partial^2 h}{\partial x^2} = \kappa\frac{\partial S}{\partial x}$
water surface
κ
h̄
S1
κ
S2
y
x
κ, sediment diffusion coefficient

Fig. 1. Definition sketches for the sediment continuity and diffusion equations used in analysing downstream changes required to bring about deposition or erosion in river channels (after Leeder & Mack, 2007). In ***SCE*** (Case A) for unconsolidated alluvium, the vector arrows show that the downstream rate of change of transport is positive and the overall term on the right hand side of the ***SCE*** is thus negative: erosion occurs along the channel reach by reworking of the river sediment bed. In ***SDE*** (Case B) a fault has caused a slope increase resulting in erosion at the slope break, with a knickpoint migrating upslope as a 'wave of incision'. Physically the downstream change of slope is positive and the diffusion equation thus causes erosion at the point of maximum curvature (slope change) which migrates upstream at a rate determined by the magnitude of curvature and sediment diffusion coefficient.

River disequilibrium: continuity and diffusional changes

Disequilibrium is demonstrated spectacularly by both downcutting to form gorges and terrace tracts and by aggradation following incorporation of excess sediment supply, as in sandar plains. Generally, downcutting or aggradation depend upon a balance between sediment brought into and taken out of a particular river reach.

Disequilibrium may be entirely dependent upon spatial gradients in mean sediment transport rate, *i*. A one-dimensional sediment continuity equation (***SCD***) can be written as in Figure 1A. Equilibrium conditions occur when $d\bar{h}/dt = 0$. A common climatic/hydrologic reason for non-zero downstream transport gradient is excess water supply relative to sediment supply or vice versa.

A second reason for non-zero downstream transport gradient involves changes brought about by either tectonic tilting or base-level fall causing a river to run over a steeper gradient reach. In both cases the gradient curvature induces excess bed shear stress, increased stream power and erosion at a rate determined by a form of sediment diffusion equation (***SDE***; Fig. 1B).

Quaternary rivers worldwide have rarely even approached equilibrium not only because of active tectonics but also rapid climate- and sea level-induced changes to variables in the ***SCE*** and ***SDE*** equations (see examples in Church & Ryder, 1972; Bull, 1979; Hereford, 1993; Blum & Tornqvist, 2000). The point is illustrated by two very large North American rivers (Fig. 2), the River Colorado and Rio Grande which between them drain much of the SW USA.

The Colorado has cut its world-famous Grand Canyon gorge into solid bedrock in response to uplifting of the Colorado Plateau relative to the normal faulted Basin and Range province (Fig. 2). The incision has propagated from a regional down-to-the-west gradient change over the Grand Wash normal fault system (Fig. 2; see Pederson *et al.*, 2002). Canyon incision corresponds to the ***SDE*** case described above and has been operative for some 20 Ma as revealed by recent high precision U-Pb dating of speleothem in perched caves (Polyak *et al.*, 2008). The scale of uplift involved arises because of active asthenospheric mantle upwelling (Roy *et al.*, 2004). Upstream incision and propagation has occurred from the bordering fault step into the uplifting plateau by a combination of eastward knick-point migration, drainage integration and gorge collapse (Hill *et al.*, 2008).

By way of contrast, the Rio Grande also flows from the eastern margin of the Colorado Plateau and the southern Rockies but does so southwards in fault-bounded rift

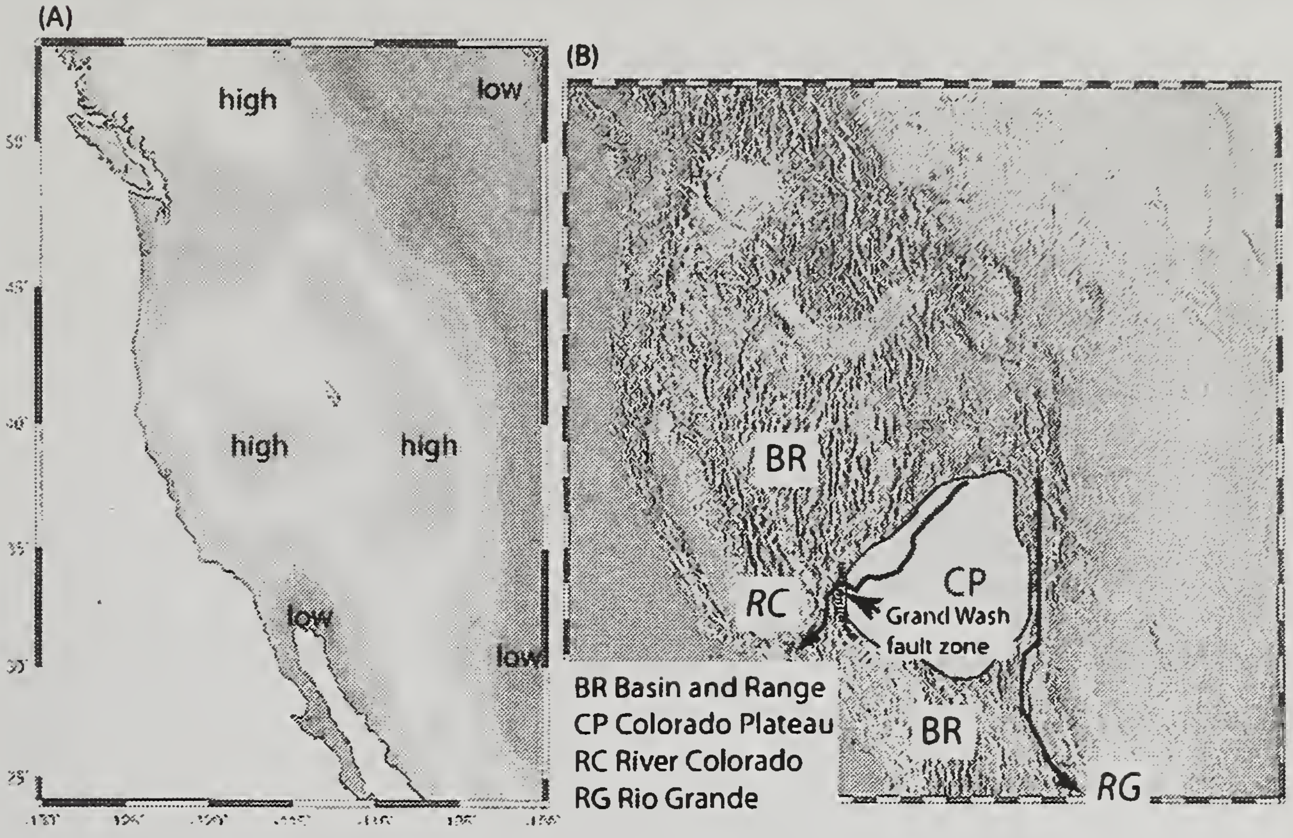


Fig. 2. A. Greyscale USGS relief maps of the SW USA B. Major tectonic provinces of the Basin and Range and Colorado Plateau, the River Colorado and Rio Grande.

basins that subside independently and relative to southward-declining regional uplift. A case for Rio Grande river incision due to climatic change is set out in more detail below.

Sediment Relaxation Time

This is the time required for a river to reach equilibrium, such that erosion and sedimentation are in balance (Paola *et al.*, 1992). It refers to the efficiency with which a river traversing any given basin can transmit depositional or erosional ′signals′ upstream, e.g. in the form of changed grain size, sediment flux or, in the cases outlined below, incision. The general concept has been used in computing the rate of upstream propagation of fluvial incision according to the ***SDE*** equation following a base level fall (Begin *et al.*, 1981; Begin, 1988; Paola *et al.*, 1991; Leeder & Stewart, 1996; Swenson, 2005). It assumes that sediment transport is linearly proportional to local bed slope, an assumption that leads to an estimate of a characteristic diffusion coefficient for the incision process. Equilibrium time, T_s, is an analogue to relaxation time in thermal systems that are cooling by conduction and is given generally by $T_s = l^2/\kappa$, where l is a length scale (downstream or upstream in this case) and κ is sediment diffusivity. Rivers with larger T_s take longer to transmit sediment signals along their length. Some of the issues arising from these concepts are outlined below.

NECESSARY CONDITIONS TO DETERMINE SURFACE UPLIFT

Since landscape incision can have numerous causes, an issue of fundamental importance when considering the possible tectonic origin of incision is *a priori* evidence for surface uplift. This requires:

1) reliable field data for the spatial and temporal extent of surface uplift.
2) time control of the duration of the uplift.
3) an absolute datum with respect to a base level such as global sea level or some other independent surface reference level.

Only then can mechanisms for surface uplift and incision be proposed and tested. It is important to realise that incised valleys and river terraces alone do NOT provide sufficient evidence to establish surface uplift. On the other hand, marine shoreline highstand deposits and terraces do provide such a datum and, once their age is established, may be used to check models for surface uplift in a rational manner.

SCE INCISION INDEPENDENT OF UPLIFT: RIO GRANDE RIFT, SW USA

Unique among large rivers of the world flowing through actively subsiding basins, the Rio Grande features spectacular exposures of its own past alluvial deposits in a deeply incised valley. Radioisotopic and magnetostratigraphic dating of these deposits prove existence of an ancestral Pliocene−early Pleistocene upper Rio Grande that flowed southwards through a series of adjacent and contiguous basins to empty into ephemeral Lake Cabeza de Vaca near the Texas-New Mexico border (Fig. 3). At around 2.25 Ma ago the lake was drained, presumably by headward cutting of an ancestral lower Rio Grande, allowing flow of a united Rio Grande to the Gulf of Mexico (Gustavson, 1991; Galloway *et al.*, 2000). The dated sedimentary records indicate mean aggradation rates for the Gilbert and Matuyama Chrons of around 0.03 mm a^{-1}, with higher rates approaching 0.07 mm a^{-1} for the Gauss interval (Mack *et al.*, 1993, 1998; Leeder *et al.*, 1996; Mack & Leeder, 1999; Leeder & Mack, 2007).

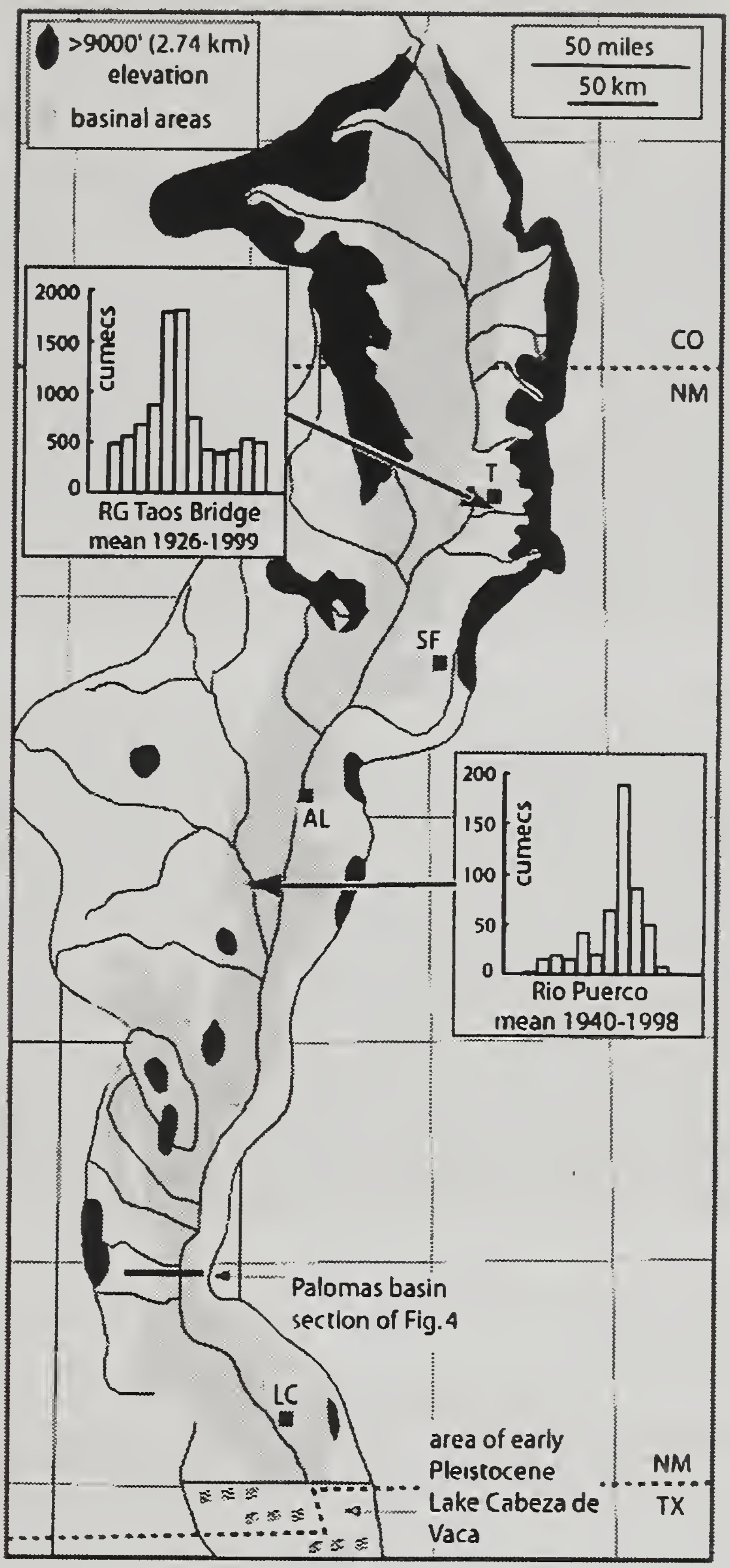

>9000' (2.74 km) elevation
basinal areas
50 miles
50 km
2000
1500
1000
500
0
cumecs
RG Taos Bridge mean 1926-1999
CO
NM
T
SF
AL
200
150
100
50
0
cumecs
Rio Puerco mean 1940-1998
Palomas basin section of Fig.4
LC
area of early Pleistocene Lake Cabeza de Vaca
NM
TX

Fig. 3. The Rio Grande catchment, tributaries, high elevation and basinal areas (after Leeder & Mack, 2007). Representative USGS long-term average mean annual discharge data (cumecs) are shown for a typical snowmelt reach (Taos Bridge gauging station, note May−June peak) compared to a summer monsoonal reach (Rio Puerco station). CO – Colorado, NM – New Mexico, TX – Texas, T – Taos, SF – Santa Fe, Al – Albuquerque, LC – Las Cruces.

Periodic incision and erosion (Brunhes Chron)

Following its aggradational phase, the ancestral Rio Grande began a periodic process of significant incision alternating with partial backfilling and inset terrace formation that has lasted to the present day (Gile *et al.*, 1981). The onset of incision is dated near the Matuyama-Brunhes chron boundary at ~0.8 Ma ago (Kortmeier, 1982; Mack *et al.*, 1993, 1998, 2002). Incision has lowered the valley floor to 100−150 m below the La Mesa geomorphic surface and palaeosol which defines the pre-incision level of the floodplain (Fig. 4). This has occurred despite fault-displacement subsidence rates of >0.1 mm a^{-1}, as evidenced by offset of middle to late Pleistocene and Holocene fan surfaces. The incision has resulted in the removal of up to 25% by volume (calculated for the Palomas basin, Fig. 4) of Pliocene−lower Pleistocene alluvium. Mean rates of incision, averaged over the entire Brunhes Chron, are in the range of 0.13-1.19 mm a^{-1}, many times that of sediment accumulation rate in the previous aggradational regime and comparable to other recent estimates of fluvial landscape incision in the wider western USA (Dethier, 2001).

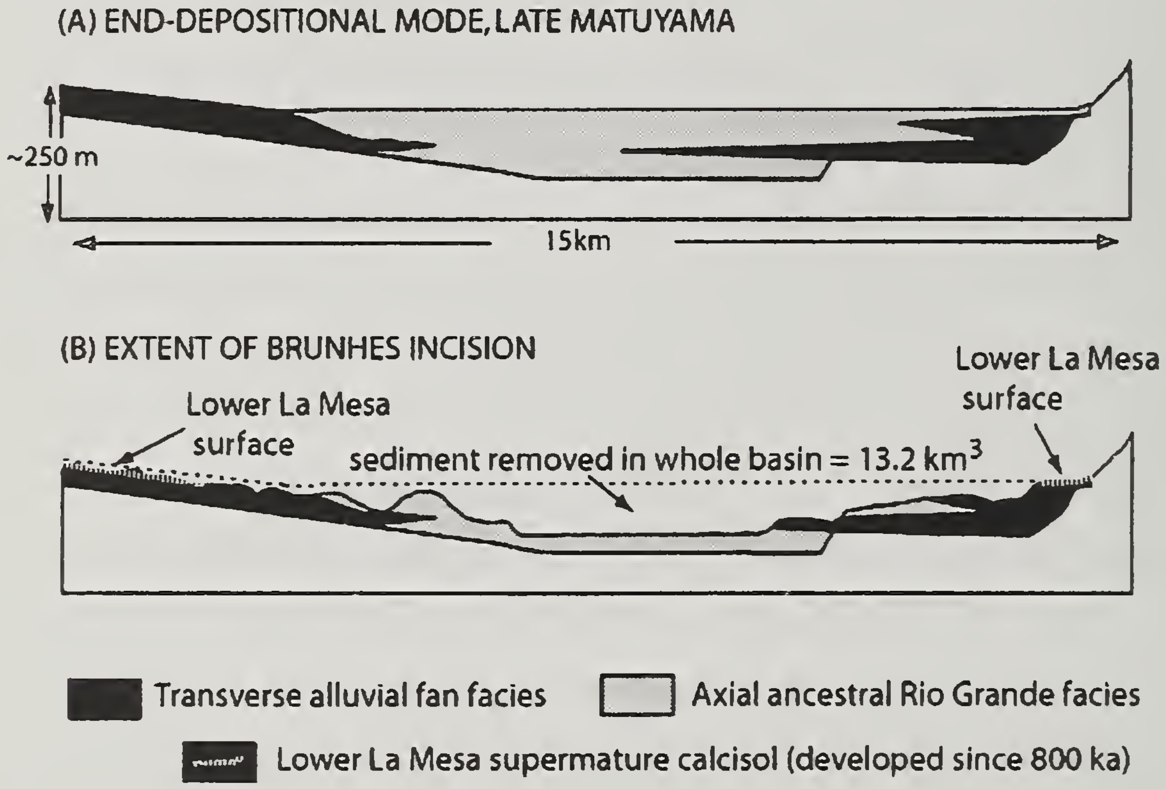

(A) END-DEPOSITIONAL MODE, LATE MATUYAMA
~250 m
15km
(B) EXTENT OF BRUNHES INCISION
Lower La Mesa surface
sediment removed in whole basin = 13.2 km³
Lower La Mesa surface
Transverse alluvial fan facies
Axial ancestral Rio Grande facies
Lower La Mesa supermature calcisol (developed since 800 ka)

Fig. 4. Restored (A) and present day (B) cross sections of the Palomas basin (see Figure 3 for location) to illustrate the extent of Brunhes incision into the Plio-Pleistocene basin fills of the southern Rio Grande rift accumulated over the previous ~ 4 Ma (Leeder & Mack, 2007; data for B from Leeder *et al.*, 1996).

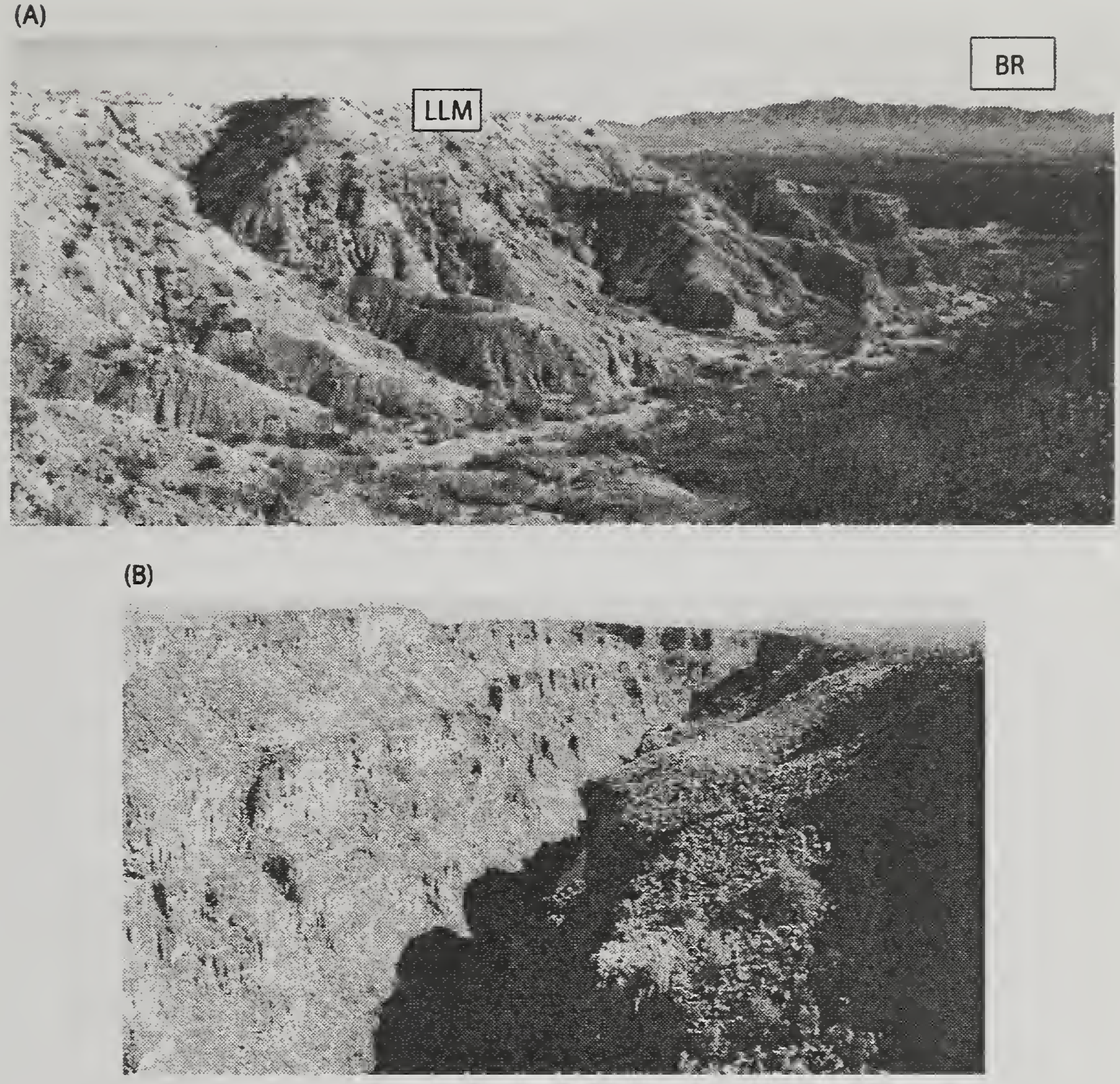


Fig. 5. Field photographs of incision in the Rio Grande rift. A. The ~ 40 m bluff of Rincon Arroyo, near Hatch, New Mexico is excavated in Matuyama-age ancestral Rio Grande axial fluvial sediment and is capped by the geomorphic surface defined by the Lower La Mesa calcrete palaeosol (LLM) dated c. 800 ka (see Fig. 4). The LLM is some 100 m above the present day level of the Rio Grande. The mountains labelled BR in the background are the southern peaks of the Black Range. B. The Rio Grande gorge, elevation 2100 m OD, at US 64 bridge north of Taos, NM. The gorge is cut into Pliocene basalt lava flows of the Taos Plateau Lavas and is c. 150 m deep at this point.

Discussion: tectonic v. climatic modes

Between 5–0.8 Ma ago, the floor of the Rio Grande rift aggraded; subsidence and sediment input from lateral sources overcame any imbalances in longitudinal gradient of transport rates. Higher aggradation rate during Gauss time (Fig. 6) may reflect higher sediment production in transverse catchments caused by a slightly moister climatic regime, as suggested by regional stable isotope studies of calcisol carbonate (Smith *et al.*, 1993; Mack *et al.*, 1994). The semi-arid palaeoclimate may have produced hydrographs including, as today (Fig. 3), contributions from both winter frontal systems, particularly in mountain catchments where (?sparse) winter snowfields could accumulate, and summer monsoon with convective precipitation in southern catchments. Relatively high sediment yields would have characterised the sparsely vegetated catchments (Fig. 5).

For the interval from 0.8 Ma to the present the whole rift periodically incised, a change contemporaneous with onset of eccentricity-driven climate cycles in the marine isotopic record (Shackleton, 1995). The incision occurred *despite* ongoing tectonic subsidence along rift boundary faults. The extreme distance of the rift from the Gulf of

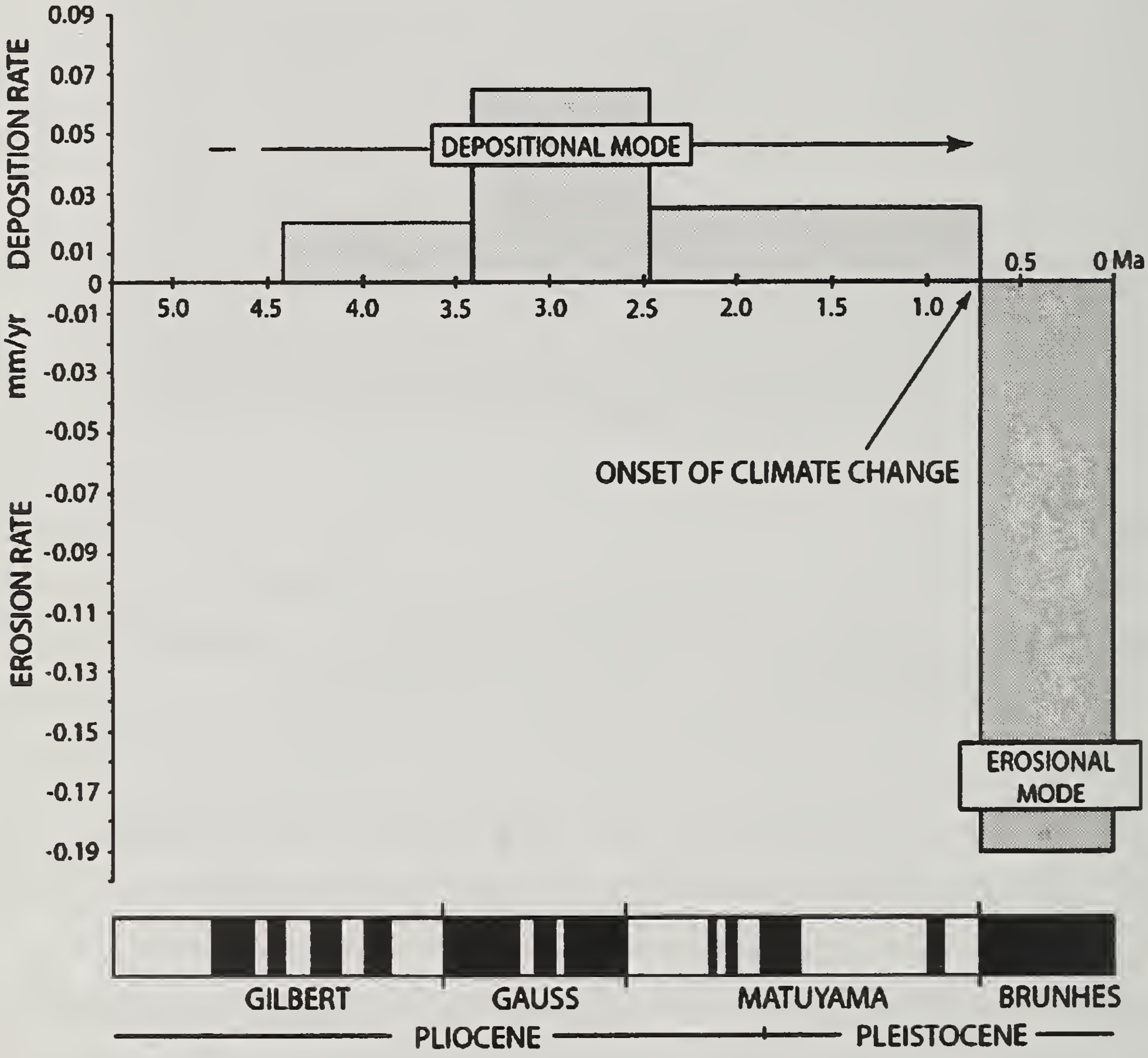


Fig. 6. Chron-averaged deposition and erosion rates derived from Plio–Pleistocene basin fill and incised valleys of southern Rio Grande rift basins.

Mexico shoreline and the absence of evidence for up-river younging of incision negate any influence of changing late-Quaternary sea levels upon this process. The climatic driver suggests that during cooler, glacial periods in the SW USA (see reviews of palaeoclimate by Thompson *et al.*, 1993; Stute *et al.*, 1995), seasonal melting of snowfields in northern catchments caused the downstream Rio Grande hydrograph to be dominated by the effects of large spring discharge peaks. Strong positive downstream sediment transport gradients led to basin incision. These were caused by a combination of: 1) substantial sediment storage in upland transverse catchments: 2) excess water discharge over sediment discharge in the channels, and; 3) relatively low sediment yields from more forested downstream catchments under cooler glacial maximum climate.

These conclusions are relevant to the determination of sediment relaxation time, T_s, for the sedimentary systems involved. In the Rio Grande rift, and probably more generally in similar Quaternary fluvial basins, the relevant length scales used to compute T_s must be extremely small. It is not so much the total length of the river channel system that should be considered, but the rapidity with which a changed discharge signal from the catchment feeder slopes can be transmitted downstream to cause channel degradation. Despite the great length of the whole river system, it is the balance between hydrological and sediment input from lateral and upstream tributaries that controls the non-uniform downstream sediment transporting capacity of the axial channel. Since there are very many tributaries draining catchments in the fault-bounded rift flanks, from Colorado to Texas, the relevant length scale is often small, ~ 10's km. At the same time, diffusivities during glacial-age spring snowmelt flooding are expected to have been very large, and hence overall relaxation times have generally been very short, perhaps of the order $10^2–10^3$ years. The situation is thus analogous to the twentieth century phase of widespread arroyo-cutting in the SW USA noted previously (e.g. Hereford, 1993).

SDE INCISION WITH TECTONIC UPLIFT: CORINTH RIFT MARGIN, CENTRAL GREECE

Southern Greece, in particular the area bordering the Gulf of Corinth (Fig. 9), is one of the world's most productive locations for the study of active continental extensional tectonics, chiefly on account of the high extension rates in the area (Davies *et al.*, 1997)

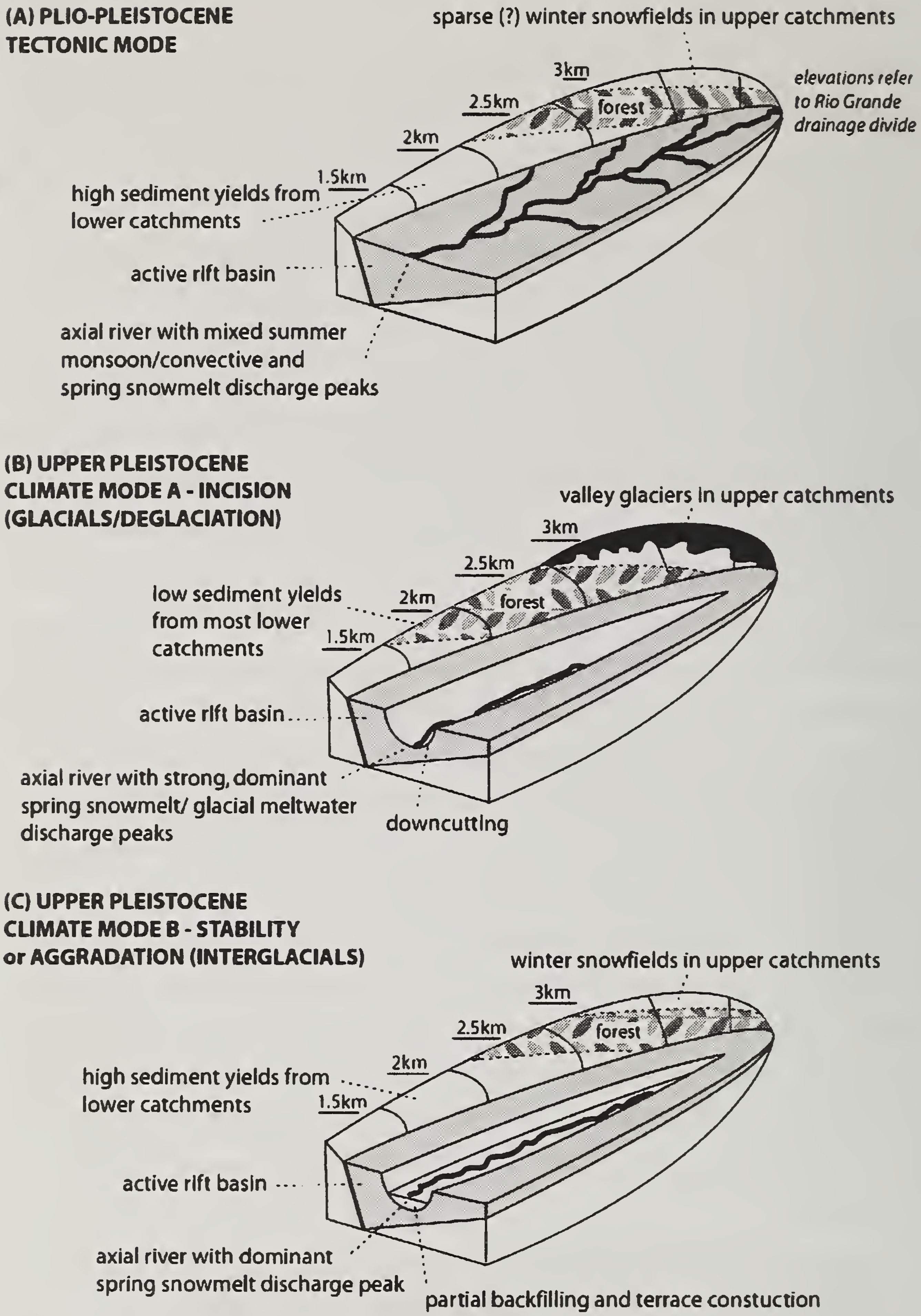

(A) PLIO-PLEISTOCENE TECTONIC MODE
sparse (?) winter snowfields in upper catchments
3km
2.5km
forest
2km
1.5km
elevations refer to Rio Grande drainage divide
high sediment yields from lower catchments
active rift basin
axial river with mixed summer monsoon/convective and spring snowmelt discharge peaks
(B) UPPER PLEISTOCENE CLIMATE MODE A - INCISION (GLACIALS/DEGLACIATION)
valley glaciers in upper catchments
3km
2.5km
forest
2km
1.5km
low sediment yields from most lower catchments
active rift basin
axial river with strong, dominant spring snowmelt/ glacial meltwater discharge peaks
downcutting
(C) UPPER PLEISTOCENE CLIMATE MODE B - STABILITY or AGGRADATION (INTERGLACIALS)
winter snowfields in upper catchments
3km
2.5km
forest
2km
1.5km
high sediment yields from lower catchments
active rift basin
axial river with dominant spring snowmelt discharge peak
partial backfilling and terrace constuction

Fig. 7. Summary of Plio–Pleistocene climatic variables affecting the Rio Grande catchment.

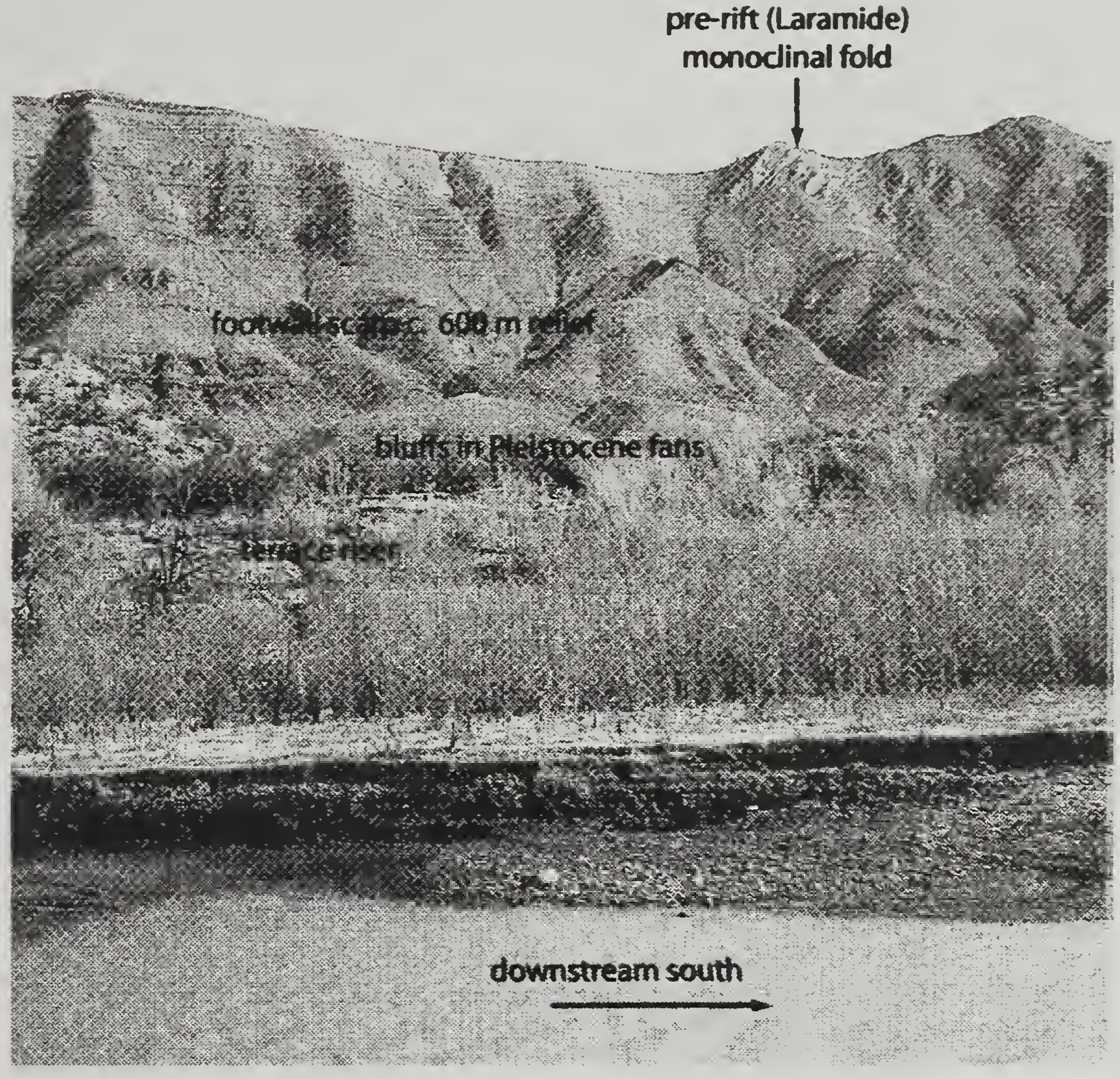


Fig. 8. View east of the Caballo Mountains (elevation 2256 m) in the footwall of the normal faulted Palomas basin of the southern Rio Grande rift (see Fig. 4). In the foreground is the Rio Grande (elevation 1275 m), with willow-vegetated floodplain, a Holocene terrace riser and prominent ~ 20 m high bluff cut into lateral alluvial fan drainage deposits.

and the exceptional clarity of field evidence for extension by normal faulting (Leeder *et al.*, 2007). The high extension rate ($3-10$ mm a^{-1}), up to two orders of magnitude greater than the Rio Grande rift, and the coastal location of the rift margin leads to an abundance of kinematic markers for surface uplift and subsidence (Fig. 10).

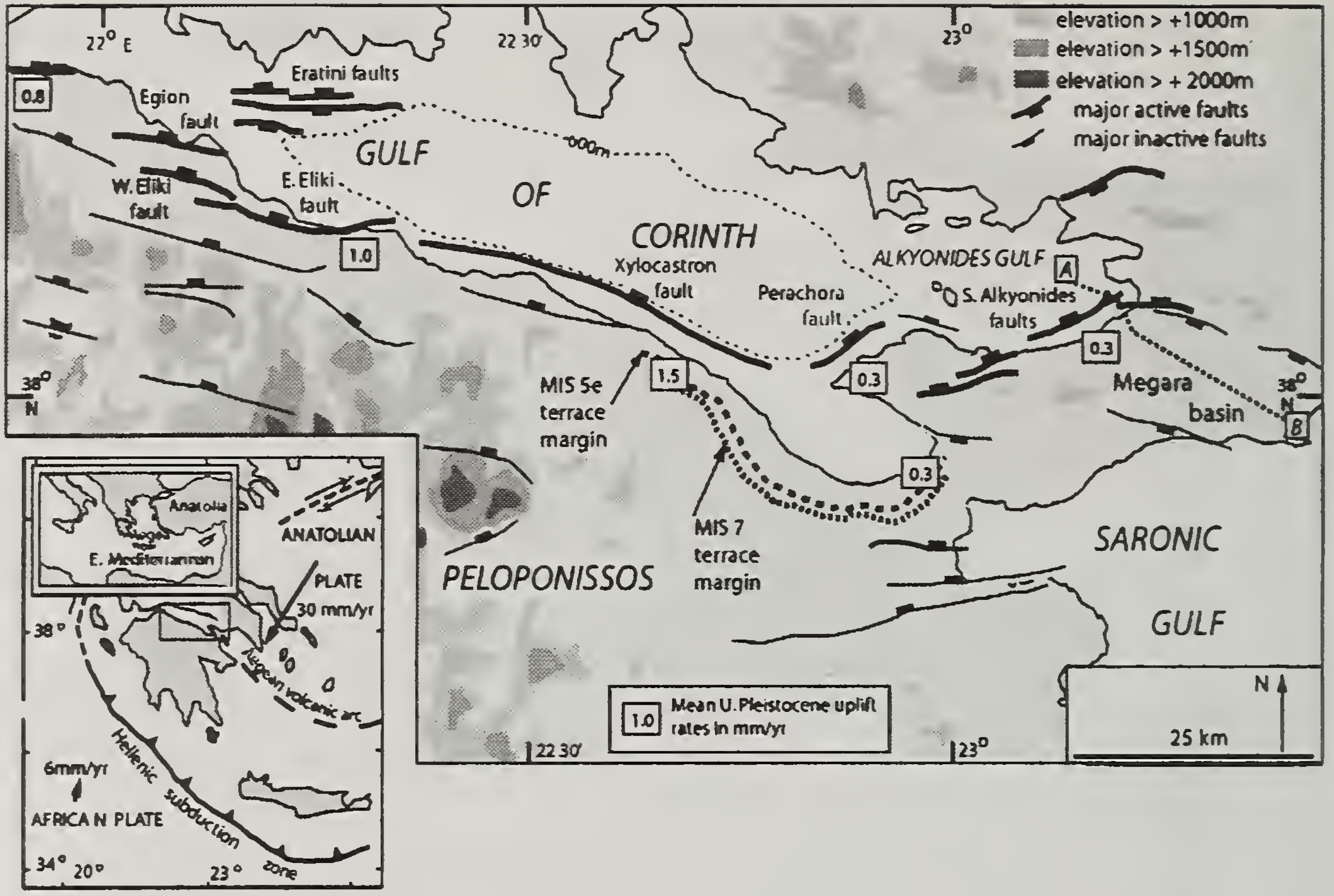


Fig. 9. General location and tectonic summary maps for Gulf of Corinth, central Greece within its Aegean context (after Leeder *et al*., 2005; Leeder & Mack, 2007). Note the suite of abandoned faults on the southern gulf margin; these are associated with abandoned, uplifting and incising basins. The dotted line A–B from the Alkyonides to Saronic gulfs denotes the line of section of Figure 12. Topography and onshore and offshore faulting after Stefatos *et al*. (2002), Leeder *et al*. (2005) and Bell et al. (2008).

A particular feature of the southern rift flank is the predominance of fluvial incision, with deep gorges (up to 800 m, see Fig. 11) cut by drainages into Quaternary sediments and Mesozoic bedrock. The origins of this fluvial incision are to be found in: 1) the uplift that has accompanied the evolution of the locus of maximum strain along the southern margin to the Gulf of Corinth and, more generally, over much of Peloponissos and; 2) northward migration of fault activity with time, witnessed by progressive abandonment, uplift and incision.

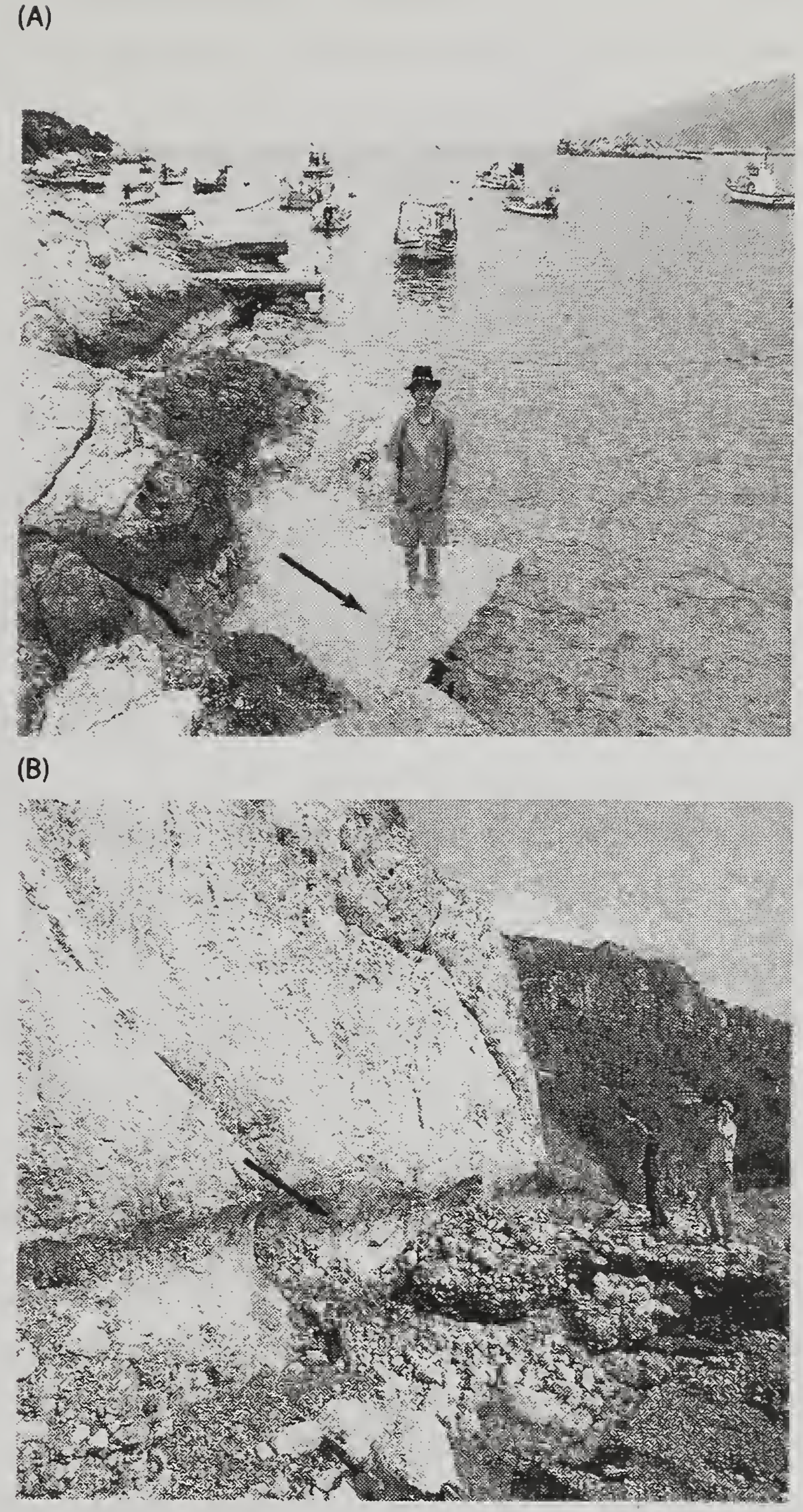


Fig. 10. Two neotectonic indicators of surface deformation from the eastern Gulf of Corinth. A) Strava, near Skinos. Author is standing on a pre-1981 concrete jetty (arrow) submerged to ~ 0.3 m below MHWM by hanging-wall subsidence during the Ms = 6.3 earthquakes of 1981 along the Skinos-Pisia fault system. Note more recent functioning jetties in background. B) Agriliou Bay, near Loutraki. GSN members Jenni Turner and Julian Andrews are looking at a mid-Holocene uplifted (c. +1.5 m elevation) shoreline notch (arrow) and are standing on its associated beachface deposits.

Origin of southern rift flank and Peloponissos uplift

The ongoing regional uplift of the southern rift flank and Peloponnisos is manifest in the widespread occurrence of deep fluvial incision and uplifting marine Neogene to Holocene sediments (e.g. Kelletat *et al.*, 1976; Keraudren & Sorel, 1987; Seger & Alexander, 1993; Kourampas & Robertson, 2000). In particular, the SE flank to the Corinth rift (Fig. 9) has a spectacular flight of uplifting marine terrace deposits that are well correlated with the global Quaternary sea-level curve (Keraudren & Sorel, 1987; Collier, 1990; Collier *et al.*, 1992; Armijo *et al.*, 1996; Leeder *et al.*, 2003, 2005; McNeill & Collier, 2004). Uplift has been ongoing for 0.6−1 Ma, based on terrace-flight elevations assuming steady uplift rate. Generally, rates of uplift decrease eastwards from ~0.7−1.5 to ~ 0.3 mm a^{-1}.

Three hypotheses have been proposed for uplift:

1) sediment underplating by intrusion and thrusting from the Hellenic subduction zone and Cretan forearc (LePichon & Angelier, 1979).
2) footwall uplift based on active coastal faults modelled in elastic half-space undergoing co- and post-seismic deformation (Armijo *et al.*, 1996).
3) a combination of regional uplift due to flat-slab subduction and local rigid-block footwall uplift (Collier *et al.*, 1992; Leeder *et al.*, 2003; Leeder & Mack, 2007).

Hypothesis 1) is unproven geophysically at the present time although there is geochemical evidence from Hellenic volcanic arc lavas for sediment assimilation. Hypothesis 2) requires excessive fault slip compared to that proven by offshore geophysical imaging (Sachpazi *et al.*, 2003). Hypothesis 3) attributes regional uplift to buoyancy of the underlying African flat slab (Fig. 10) and local footwall uplift along the active southern rift-margin faults (Leeder & Mack, 2007).

Sedimentary consequences of fault abandonment and uplift

Whatever the exact mode of fault abandonment and propagation, uplift acted to create slope discontinuities and knickpoints at positions where newly propagated faults were crossed by drainages issuing from antecedent valleys. This had the effect of eroding previously deposited sediments and renewing upstream propagation (according to the workings of the ***SDE*** described earlier, Fig. 1B) of progressively younger knickpoints after each episode of normal faulting. In addition, upstream-migrating waves of fluvial incision would also have been produced during repeated glacial lowstands as drainages adjusted to slope changes at former highstand shorelines. In both cases winter-wet glacial

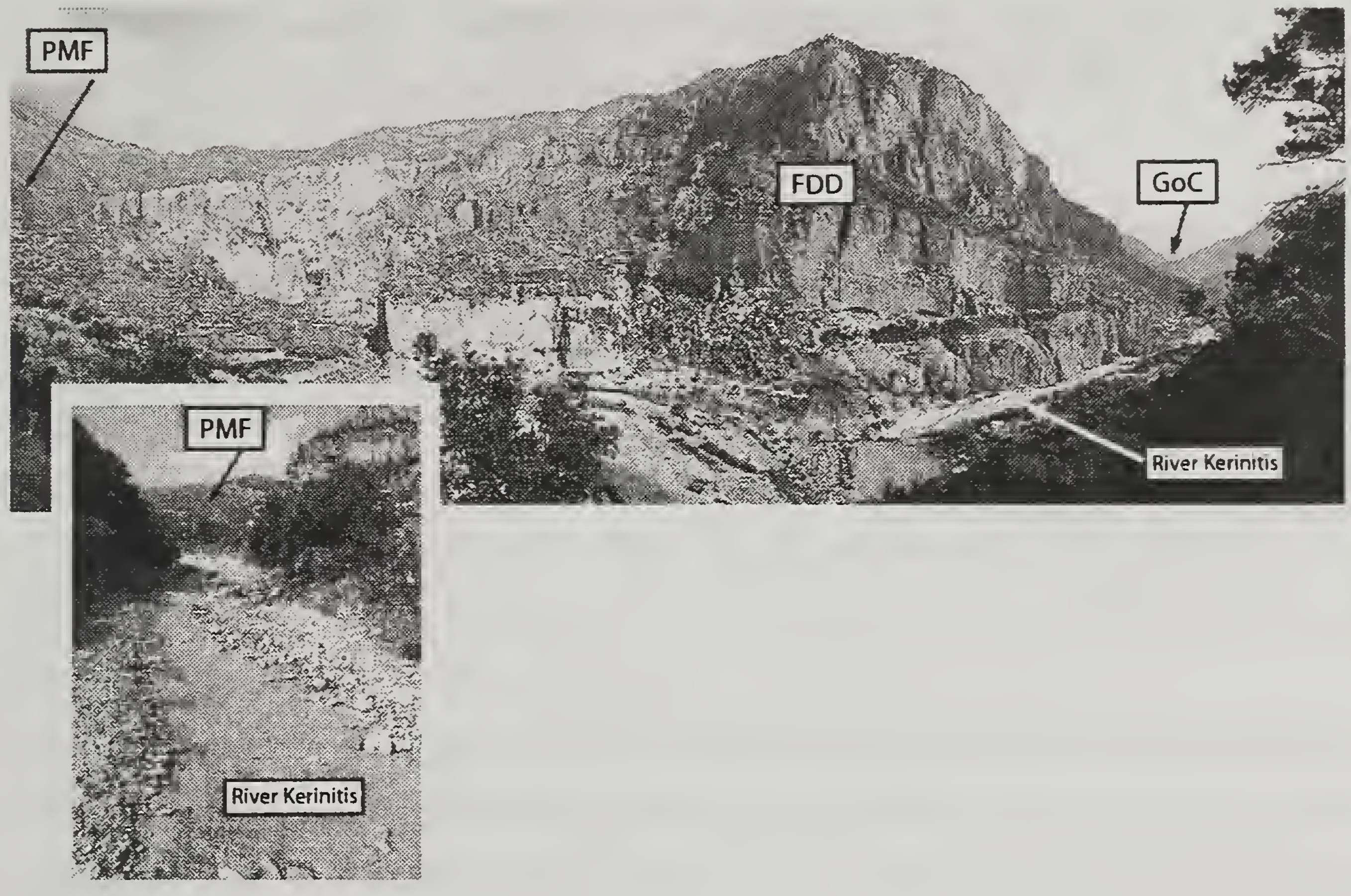


Fig 11. ***CDE***-type incision in the uplifting northern Peloponnissos. Shown here in the main view is the c. 600 m deep Kerinitis gorge cut into uplifted and eroded Pleistocene fan delta deposits (FDD). These accumulated at the formerly active faulted margin to the deep Gulf of Corinth (GoC), defined as the hangingwall to the mid-Pleistocene active Pirgaki–Mamoussia fault (PMF). Inset shows the modern river in its gorge and an upstream view to the Pleistocene fault.

climates in Greece (Leeder *et al.*, 1998; Collier *et al.*, 2000) would have led to increased erosion potentials and diffusivities during such times. Over <1 Ma, the net effect has been to produce spectacular gorges (Fig. 11) with ~ 800 m of relief, and recycling of eroded earlier syn-rift sediment as fan deltas and submarine fans into the active rift. As noted above, footwall incision in the Megara basin over the past 2 My or so has been accompanied by significant backtilting and drainage reversal (Fig. 12).

Regarding the sediment relaxation time, T_s, for the Gulf of Corinth rift, the physical length scale from catchment to ocean is low ~ 30 km. This, combined with a very high diffusivity and strain rate (an order of magnitude greater than in the Rio Grande rift), causes erosion across rapidly vertically-growing normal faults to be very large and hence sediment relaxation time to be low.

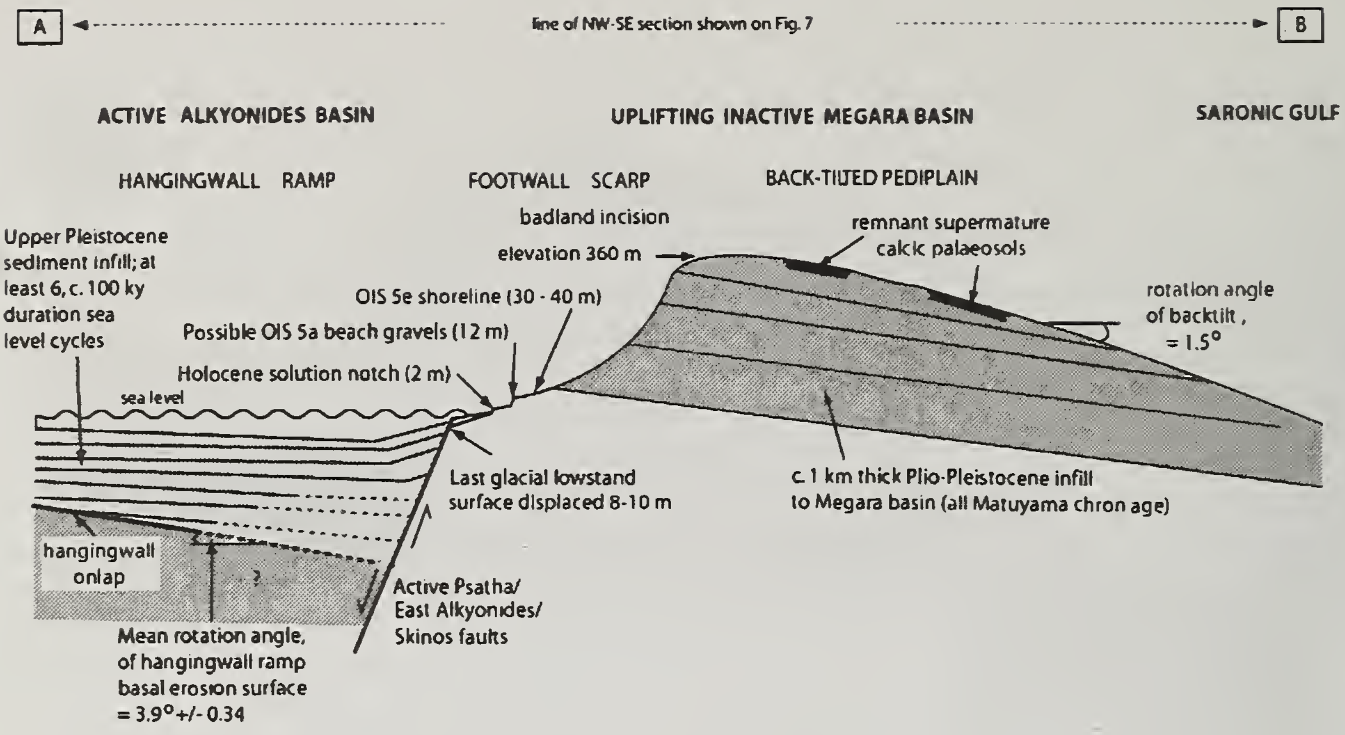

A
line of NW-SE section shown on Fig. 7
B
ACTIVE ALKYONIDES BASIN
UPLIFTING INACTIVE MEGARA BASIN
SARONIC GULF
HANGINGWALL RAMP
FOOTWALL SCARP
BACK-TILTED PEDIPLAIN
badland incision
elevation 360 m
remnant supermature calcic palaeosols
Upper Pleistocene sediment infill; at least 6, c. 100 ky duration sea level cycles
OIS 5e shoreline (30 - 40 m)
Possible OIS 5a beach gravels (12 m)
Holocene solution notch (2 m)
sea level
rotation angle of backtilt, = 1.5°
Last glacial lowstand surface displaced 8-10 m
c. 1 km thick Plio-Pleistocene infill to Megara basin (all Matuyama chron age)
hangingwall onlap
?
Active Psatha/ East Alkyonides/ Skinos faults
Mean rotation angle, of hangingwall ramp basal erosion surface = 3.9°+/- 0.34

Fig. 12. Schematic section along the line A–B in Figure 10 across the eastern part of the Gulf of Corinth to show: 1) the young, active, offshore Psatha/East Alkyonides fault bounding the Alkyonides Gulf; 2) the abandoned, uplifting and incising Pleistocene Megara basin (after Leeder *et al.*, 2005); and 3) major morphological features useful in parameterization of rates of uplift and subsidence associated with displacements along the active faults.

UPPER PLEISTOCENE UPLIFT OF EAST ANGLIA

Evidence and its context

Although general and prolonged Quaternary surface uplift has been invoked to cause river incision in the SE British Isles (Maddy, 1997, 1998; Maddy & Bridgland, 2000; Maddy *et al.*, 2000, 2001; Westaway *et al.*, 2002), no direct evidence for such uplift has been advanced. Further, the physical mechanism proposed (Westaway *et al.*, 2002) is flawed, a topic returned to in a later section. However, unique in the Quaternary record of southern Britain, the marine Crag formations of East Anglia provide a clear datum for use in uplift studies. The structure contour map for the base of the marine Norwich Crag first drawn by Funnell (1961) provides an indication of relative sea level change since the time of early Crag deposition in the late-Pliocene Tiglian stage, c. 2 Ma ago (Funnell, 1995; 1996). Since the global oxygen isotope record provides no significantly higher (i.e. > ~ 5 m) sea level since that time (see compilations by Head & Gibbard 2005) it follows *a priori* that elevation of the Crag must be due to tectonic uplift (Read et al. 2007). This conclusion was well known to Funnell himself, though he puzzled on this and no specific mechanism for the uplift has been forthcoming.

Timing of the uplift

Progress made in recent years with the East Anglian Quaternary includes recognition of marine nearshore deposits younger than the Norwich Crag but older than unequivocal Anglian-age glacial deposits (see Rose *et al.*, 2002). These occur in the Wroxham Crag Formation, notably in the Chapel Hill marine sands which occur at elevations ~ +30 m OD around Norwich (Read *et al.*, 2007); and at Pakefield, Suffolk (Parfitt *et al.*, 2005) at maximum elevations of ~ +10 m OD. Marine tidal sedimentary deposits also overlie the Cromerian complex up to elevations of ~ +5 m OD at several locations on the north Norfolk coast, most notably at West Runton.

In their important paper Read *et al.* (2007) determine that the marine Chapel Hill sands underlie the local Anglian till, stating: "*... in excess of 30 m of uplift must have occurred in the region of Norwich, since deposition of the Chapel Hill sands*", with indirect evidence for the age of the Chapel Hill sands implying "*.. uplift in excess of 30 m ... over the last c. 600/500 ka ...*" and with spatial variations in the elevation of equivalent coastal deposits at localities such as the Norwich Crag at West Runton, Norfolk implying "*... neotectonics in northern East Anglia have been differential, with at least c. 30 m more uplift around Norwich than further northeast*".

The surface uplift clearly either coincides with, or post-dates, the Anglian ice advance during MIS 12, ~ 400 ka ago. The spatial pattern of uplift must follow the regional trend of base-Norwich Crag structure contours, with an extra increment to allow for the 10 m or so interval to the top of the youngest marine Wroxham Crag. The pattern strongly suggests that arcuate easterly tilt is responsible, with a locus of maximum amplitude >30 m somewhere to the west of central Norfolk.

Cause of East Anglian uplift: Anglian ′icy bulldozer′

The timing, extent, magnitude and permanence of the uplift noted above lead to the conclusion that a regional event is responsible. This cannot have been mere ice loading and unloading for such crustal motions are transient; the associated isostatic upwarps and downwarp are reversed during meltout. Also, far-field effects from sediment loading in the adjacent central or southern North Sea basin date back to earlier in the Neogene and do not explain the regional uplift pattern of easterly tilt.

For a reason to initiate permanent uplift and easterly tilt about a N–S axis we need look no further than the massive rock excavations demonstrated quantitatively by Clayton (2000) during advance of Anglian ice lobes across the N–S to NE–SW trending upper Mesozoic escarpment of SE Lincolnshire, W Norfolk, W Suffolk and E Cambridgeshire (Fig. 13). Making certain reasonable assumptions about the form of the pre-Anglian scarp-and-vale topography over this 7.5×10^3 km^2 area, computed rock budgets for this, the *Clayton Event*, named after its first quantifier, are:

A – U Jurassic mean erosion ~ -60 m;
B – Chalk scarp mean erosion ~ -66 m;
C/D– Anglian Chalky Till mean deposition ~ +27 m,

with the deficit between erosion and deposition due to export in Anglian meltwater (Clayton, 2000). Taking the pre-Chalk substrate and scarp relief together it appears that mean erosion over a substantial area was ~ 100 m.

Mechanism for uplift

The Clayton Event has a solid earth implication in that geologically-rapid removal of rock on such a scale would cause permanent uplift after the transient effects of Anglian ice loading and unloading were removed. It is an example of *denudational isostasy*, a mechanism long-proposed world-wide but only confirmed by apatite fission-track dating from examples such as the Appalachian mountains in the 1980s (Pavich, 1985, 1986). For ~ 100 m of crustal unloading due to Anglian glacial erosion, simple Airy isostatic compensation by inflowing mantle (Fig. 14) will generate ~ 75 m of permanent surface uplift over the area of erosion. Approximate assumptions based on post-glacial ice sheet unloading rates indicate times ~ 10^4–10^5 years might see an appreciable portion of Airy isostatic uplift achieved at mean rates ~ 1–10 mm a^{-1}. Solution of the ′wider uplift′ problem needs to take account of the fact that the uplift extends far to the east of the computed extent of heavily-eroded Mesozoic substrate (Figs 13–15) and implies one or more of the following, in increasing order of probability:

1) an excess of viscous mantle flow occurred over that required to locally compensate for erosion. This may be due in part to the asymmetry of rock removal, with higher mass

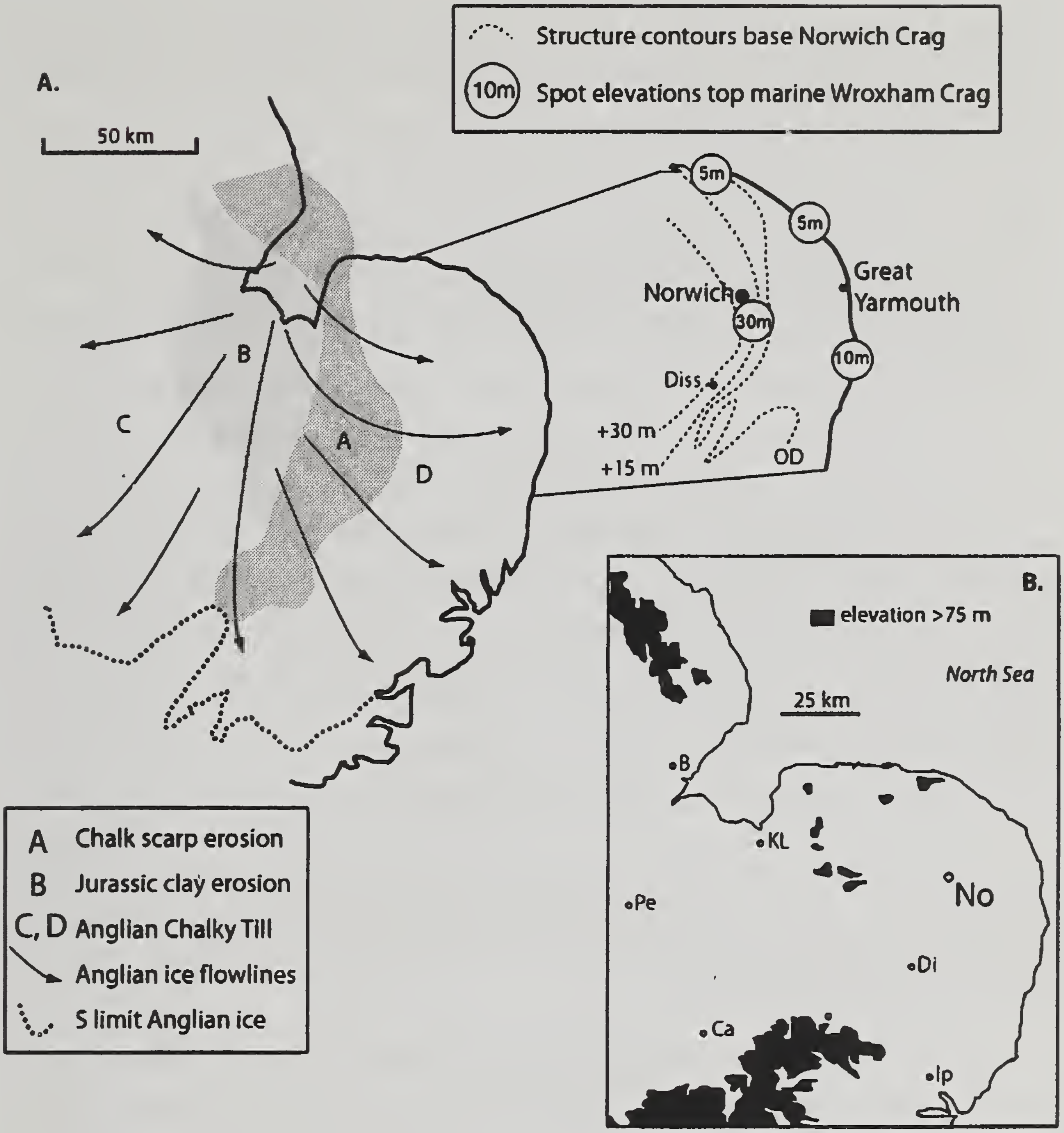


Fig. 13. A) The areas of 'greater East Anglia' affected by severe erosion of bedrock during advance of Anglian ice (after Clayton, 2000). Inset shows structure contours on the base marine Norwich Crag (after Funnell, 1961) and spot heights for maximum elevation of marine Wroxham Crag (mostly after Read *et al.*, 2007; Parfitt *et al.*, 2005). B) Conspicuous elevation gap in the Cretaceous Chalk escarpment between Bury St Edmunds and south Lincolnshire excavated by Anglian ice.

per unit area extracted along the Cretaceous scarp compared with that over Upper Jurassic claylands to the west (see Watts *et al.*, (2001) for a discussion of this aspect with reference to Cotswolds scarplands). Such asymmetry may have controlled the pressure gradients responsible for compensatory incoming viscous channel flow in the mantle, or

2) there was significant extra glacial erosion in the meridional area between the western scarplands and Norwich,

or

3) flexure arising from upward bending motion of the eroded elastic lithosphere during isostatic recovery played a significant role in the process of permanent uplift (Fig. 14).

Flexural response to denudation

For initial progress with a flexural solution, we can adapt the approach used by Lane *et al.* (2008) to assess the uplift of Jurassic limestone scarplands arising from gradual erosional denudation by the rivers Severn and Avon of adjacent clay vale lowlands in the greater Cotswold area. The 2D (*xy* plane) flexural rebound expected after erosion of sediments is calculated using,

$$R(k) = S(k)\frac{\rho s}{\rho m}\phi(k)$$

where $R(k)$ and $S(k)$ are the Fourier transforms of the rebound and unload distribution respectively, ρ_s and ρ_m are sediment and mantle density (2500 and 3300 kg m^{-3} respectively) and $\phi(k)$ is given by

$$\phi(k) = \left[\frac{Dk^4}{g\rho m} + 1\right]^{-1}$$

$$D = \frac{T_e{}^3 E}{12(1-\nu^2)}$$

where D is flexural rigidity, k is wavenumber vector $(k_x^2+k_y^2)^{0.5}$, g is gravitational acceleration, T_e is elastic thickness, E is Young's Modulus and ν is Poisson's ratio. Realistic values for the straightforward crustal elastic parameters are taken from Lane *et al.* (2008, Table 2) and the more problematic T_e is taken as about 5 km from recent estimates for the British lithosphere (Tiley *et al.*, 2003). Lane et al. found that the ratio of maximum flexural uplift, $H_{n(\max)}$, to mean excavation, H_e, for an excavation width, W = 60 km, and excavation depths, 200-500 m, has a constant ratio of around $H_{n(max)}/(H_e)$ = 0.4, decaying to a zero uplift asymptote at distance >>1W. For the East Anglian escarpment the erosional parameters of Clayton (2000, Table 3) are used and it is assumed that the constant ratio, $H_{n(max)}/H_e$, applies to shallower excavation depths than those modelled by Lane et al. (2008) so that H_e = ~ 100 m. For a mean W of ~ 60 km this yields $H_{n(max)}$ = ~ 40 m. This figure is clearly of the right order to explain the magnitude of elevation change (>30 m) and spatial wavelength (~ 60-80+ km?) of post-Anglian ′flank′ uplift of marine late-Quaternary deposits east of the excavated Chalk escarpment.

It is also important to constrain the boundaries to far-field deformation over the time elapsed since glacial excavation. This should be possible by a consideration of the elevation and distribution of former coast lines such as that of the last interglacial. The elevation of this in areas unaffected by surface uplift should be ~ +5m OD according to the marine oxygen isotope curve. Current far-field limits can be defined in S Devon (Mottershead *et al.*, 1987, although the shorelines are as yet undated) and E Yorkshire (Bateman & Catt, 1996). Closer to home a shoreline along the N Norfolk coast between Morston and Stiffkey (Solomon, 1932; Gale *et al.*, 1988; Gale & Hoare, 2007) reaching up to about +5m OD has been ascribed to MIS 5e, although it has yet to be directly dated. It seems to indicate no significant post-MIS 5e shoreline elevation change, suggesting that permanent surface uplift may have been accomplished before the last interglacial.

Future uplift modelling should seek to investigate:

1) the detailed flexural elastic and viscoelastic response of the crust and mantle to erosion.
2) transient flow due to Anglian and Devensian ice lobe advances and meltouts.
3) probable contiguous uplift of areas west of the excavated Mesozoic rocks in the East Midlands (Fig. 14), though this will prove difficult because of the lack of datum with which to assess surface uplift.
4) permanent loading of the crust due to the great Anglian moraines of the N Norfolk (Holt–Cromer) ridge.

Further implications of East Anglian landscape tilting

1) If flexural tilt occurred during the interval 400-130 ka it is not strictly *neo*tectonic if that term is a synonym for *active* tectonics. However, although there is no hard-and-fast definition of neotectonic in the literature, it is A.B. Watts` opinion (pers. comm. June 2008) that elastic flexure should not be regarded as a neotectonic process in any case since it is mainly concerned with very gently bending crustal rocks, not breaking them.

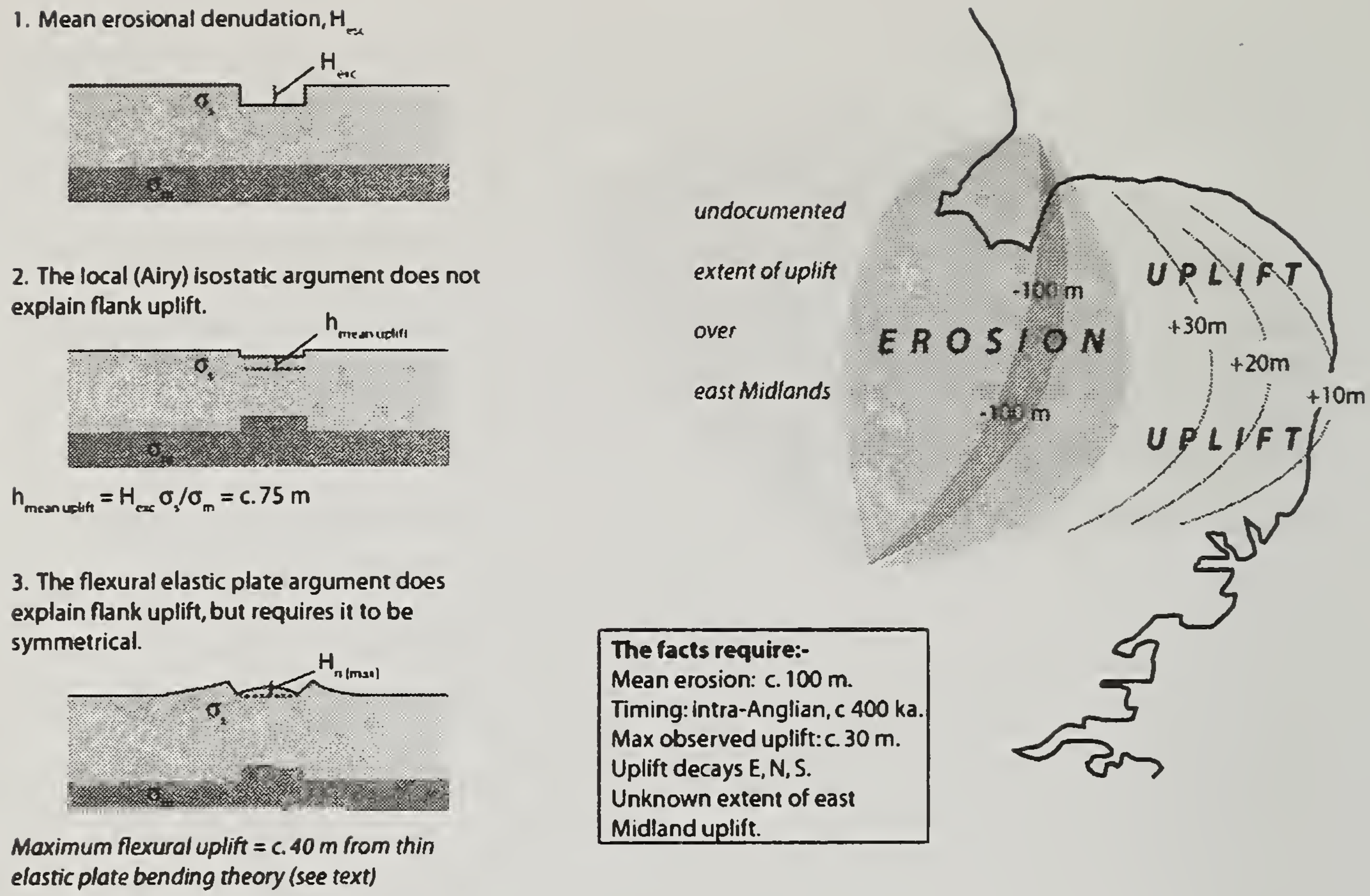

1. Mean erosional denudation, H_{exc}
H_{exc}
σ_s
σ_m
2. The local (Airy) isostatic argument does not explain flank uplift.
$h_{mean\ uplift}$
σ_s
σ_m
$h_{mean\ uplift} = H_{exc}\,\sigma_s/\sigma_m$ = c.75 m
3. The flexural elastic plate argument does explain flank uplift, but requires it to be symmetrical.
$H_{n\ (max)}$
σ_s
σ_m
Maximum flexural uplift = c.40 m from thin elastic plate bending theory (see text)
undocumented
extent of uplift
over
east Midlands
-100 m
EROSION
-100 m
UPLIFT
+30m
+20m
+10m
UPLIFT
The facts require:-
Mean erosion: c. 100 m.
Timing: intra-Anglian, c 400 ka.
Max observed uplift: c. 30 m.
Uplift decays E, N, S.
Unknown extent of east Midland uplift.

Fig. 14. Simple statements of the Airy isostatic and flexural elastic relaxation models for 'greater East Anglian' rock uplift following Anglian ice sheet erosion of Mesozoic scarpland bedrock and subsequent transient relaxation of glacial loading/unloading. The contours show an indication of the magnitude of permanent uplift of coastal marine Crag horizons in East Anglia (see Fig. 13).

2) It is possible that E to SE flow of the main modern Norfolk and Suffolk drainages into the southern North Sea (Fig. 15) came about partly by superimposition upon the tilted post-Anglian till landscape. River flow also occurred from western East Anglia into the erosional claylands of the Wash embayment. Quantitative landscape models may be able to reproduce the two effects given knowledge of the gradients and time intervals involved.

3) Tilting was probably not the direct cause of post-Anglian landscape incision. Development of estuaries, incised valleys and post-Anglian terraces in East Anglia are more likely to have been due to intrinsic riverine variables as outlined generally for the ***SCE*** case above or to the ***SDE*** effect acting upon gradient changes accompanying post-Anglian lowstand sea levels. The latter is considered of less importance because of the

tiny gradient changes and low diffusivities involved, leading to expectation of long sediment relaxation times for East Anglian rivers.

4) Uplift may have lead to minor brittle failure along 'blind' basement faults over the wider East Anglian area (a suggestion made in the oral discussion of my Presidential Address by Adrian Read).

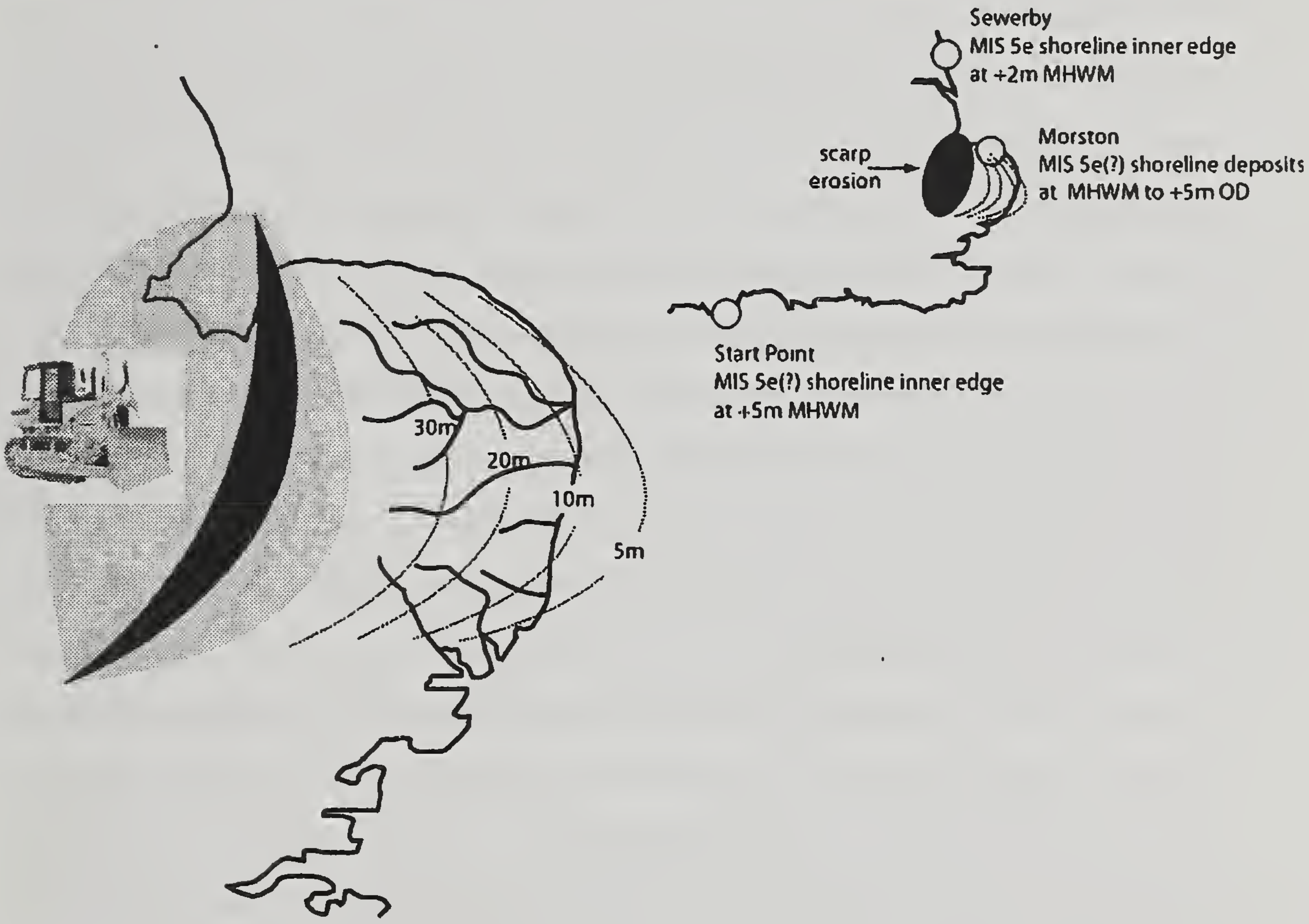


Fig. 15. Summary of East Anglian uplift and regional drainages that may have flowed E to SE due to post-Anglian tilting. Inset shows far field context involving the essential stasis of suspected MIS 5e shorelines in south Devon, and north Norfolk. The east Yorkshire shoreline is directly dated to MIS 5e (Bateman & Catt, 1996).

Quaternary river terraces and surface uplift over wider S England

Some fluvial geomorphologists (Maddy, 1997, 1998; Antoine *et al.*, 2000; Maddy & Bridgland, 2000; Maddy *et al.*, 2000, 2001; Westaway *et al.*, 2002) have assumed that late Quaternary river terraces of S England and northern mainland Europe provide *a priori* evidence for surface uplift by tectonics. A specific hypothesis to explain this uplift is the notion that to-and-fro creeping flow of lower crustal rock and resultant transfer of thermal energy has occurred in response to pressure gradients caused by late Quaternary sea level oscillations (Westaway *et al.*, 2002). This is postulated to cause permanent deformation at continental margins. There are a number of objections to this imaginative hypothesis, including:

1) the eustatic driving mechanism proposed is universal and should therefore affect each coastline in the world not affected by other tectonic processes. No such universal uplift of otherwise stable coastlines is seen. For example we have already noted that the coasts of E Yorkshire and SW England have last interglacial shorelines at approximately the MIS 5e highstand level of +5m OD. The crustal creep driving mechanism causes uplift rates of ~ 0.1 mm a^{-1} (Westaway *et al.*, 2002), requiring that these shorelines be at least +15 m OD. MIS 5e shorelines at +5m also occur further afield around the non-glaciated European coast, as observed extensively by the author in the stable tectonic massif of NW Spain (Galicia).
2) computed rates of creeping flow are far too low to have been forced by hydro-eustasy. Simple principles of Poiseuille flow (Westaway *et al.*, 2002) predict the lower crustal channel creep velocity as, $u_c = \mathrm{d}p/\mathrm{d}x\ (h_c^2/12\mu_e)$, where the differential is longitudinal pressure gradient maintained by a 100 m sea level fluctuation, h_c is the thickness of the creeping flow ′channel′ and μ_e is the effective viscosity of the channel rock. Taking $\mathrm{d}p/\mathrm{d}x = 5$ Pa m^{-1}, $h_c = 10$ km and $\mu_e = 6.\ 10^{17}$ Pa s (data from Appendix A4 of Westaway *et al.*, 2002) gives $u_c = 2.2.\ 10^{-3}$ m yr^{-1}. On the timescale of a half eccentricity cycle this equates to only 110 m per 50 000 years, a rate that fails by >3 orders of magnitude to allow significant material and thermal transport and permanent isostatic surface uplift.
3) the bathymetry of the southern North Sea (< 30 m) is too shallow for the full effects of glacio-eustasy to have caused pressure gradients to drive crustal flow inwards and outwards from SE Britain and NW Europe. Any further provenance

of lower crustal flow, say from the Atlantic coasts, seems impossible given the velocity and thermal timescales involved.

4) any very slow creeping flow in and out of the North Sea or Celtic Sea areas due to sea level forcing will have been overridden by vastly more efficient and reversible mantle creep processes arising from glacio-isostasy.

ACKNOWLEDGEMENTS

Thanks go to the Committee of the Geological Society of Norfolk for inviting me to be Honorary President in this the 40th anniversary of the founding of the Society from the old Paramoudra Club, a neglected *événement* that much occupied me in 1968 when I was a youthful last General Secretary of the club. I am grateful to Julian Andrews for encouragement to write my Presidential lecture up as a paper and to Jennifer Mason for enjoyable field excursions to examine key localities. I thank referees Tony Watts and Peter Hoare for their interest and for very many useful suggestions that much improved an earlier version of this paper. On a personal note, I first studied geology in the much-loved but now demolished 'House' laboratories above the prefects' suite at the City of Norwich School between 1964 and 1966. The cut-and-thrust of geological debate in classroom and field with my peers and teachers in the school branch of the old Paramoudra Club were a great influence on me. I therefore dedicate this paper to them and their geological descendants: *Floreat Geologia Ager Norvicensis*!

REFERENCES

ANTOINE, P., LAUTRIDOU, J.P. & LAURENT, M. 2000. Long-term fluvial archives in NW France: response of the Seine and Somme rivers to tectonic movements, climatic variations and sea-level changes. *Geomorphology*, **33**, 183-207.

ARMIJO, R., MEYER, B., KING, G.C.P., RIGO, A. & PAPANASTASSIOU, D. 1996. Quaternary evolution of the Corinth Rift and its implications for the late Cenozoic evolution of the Aegean. *Geophysical Journal International,* **126**, 11-53.

BATEMAN, M.D. & CATT, J.A. 1996. An absolute chronology for the raised beach and associated deposits at Sewerby, East Yorkshire, England. *Journal of Quaternary Science*, **11**, 389-395.

BEGIN, Z.B., MEYER, D.F. & SCHUMM, S.A. 1981. Development of longitudinal profiles of alluvial channels in response to base level lowering. *Earth Surface Processes and Landforms*, **6**, 49-68.

BEGIN, Z.B. 1988. Application of a diffusion-erosion model to alluvial channels which degrade due to base-level lowering. *Earth Surface Processes and Landforms*, **13**, 487-500.

BELL, R.E., McNEILL, L.C., BULL, J.M. & HENSTOCK, T.J. 2008. Evolution of the offshore western Gulf of Corinth. *Bulletin of the Geological Society of America*, **120**, 156-178.

BLUM, M.D. & TÖRNQVIST, T.E. 2000. Fluvial responses to climate and sea-level change: a review and look forward. *Sedimentology*, **47** (suppl. 1), 2-48.

BULL, W.B. 1979. Threshold of critical stream power in streams. *Geological Society of America Bulletin*, **90**, 453-464.

CHURCH, M. & RYDER, J.M. 1972. Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. *Geological Society of America Bulletin*, **83**, 3059-3072.

CLAYTON, K.M. 2000. Glacial erosion of the Wash and Fen basin and the deposition of the chalky till of eastern England. *Quaternary Science Reviews*, **19**, 811-822.

COLLIER, R.E. Ll. 1990. Eustatic and tectonic controls upon Quaternary coastal sedimentation in the Corinth basin. *Journal of the Geological Society, London*, **147**, 301-314.

COLLIER, R.E. Ll., LEEDER, M.R., ROWE, P.J. & ATKINSON, T.C. 1992. U-series dating and tectonic uplift of Upper Pleistocene marine sediments from the Corinth and Megara Basins, Greece. *Tectonics*, **11**, 1159-1167.

COLLIER, R.E.Ll., LEEDER, M.R., TROUT, M., FERENTINOS, G., LYBERIS, E. & PAPATHEODOROU, G. 2000. High sediment yields and cool, wet winters during the last glacial lowstand, northern Mediterranean. *Geology*, **28**, 999-1002.

DAVIES, R., ENGLAND, P., PARSONS, B., BILLIRIS, H., PARADISSIS, D. & VEIS, G. 1997. Geodetic strain of Greece in the interval 1892–1992. *Journal of Geophysical Research*, **102**, 24 571-24 588.

DETHIER, D.P. 2001. Pleistocene incision rates in the western United States calibrated using lava Creek B tephra. *Geology*, **29**, 783-786.

FUNNELL, B.M. 1961. The Palaeogene and Early Pleistocene of Norfolk. In: Larwood, G.P. & Funnell, B.M. (eds.) *The Geology of Norfolk*, 340-364.

FUNNELL, B.M. 1995. Global sea-level and the (pen-)insularity of late Cenozoic Britain. In: Preece, R.C. (ed.) *Island Britain: a Quaternary perspective*. Geological Society of London, Special Publication, **96**, 3-13.

FUNNELL, B.M. 1996. Plio-Pleistocene palaeogeography of the Southern North Sea Basin (3.75–0.60 Ma). *Quaternary Science Reviews*, **15**, 391-405.

GALE, S. J., HOARE, P.G., HUNT, C.O. & PYE, K. 1988. The Middle and Upper Quaternary deposits at Morston, north Norfolk, U.K. *Geological Magazine*, **125**, 521-533.

GALE, S.J. & HOARE, P.G. 2007. The glacial stratigraphy of lowland southern and eastern Britain: temperate-stage deposits at Morston and Kirmington. *Proceedings of the Yorkshire Geological Society*, **56**, 245-252.

GALLOWAY, W.E., GANEY-CURRY, P.E. LI, X. & BUFFLER, R.T. 2000. Cenozoic depositional history of the Gulf of Mexico Basin, *Bulletin American Association of Petroleum Geologists*, **84**, 1743-1774.

GILE, L.H., HAWLEY, J.W. & GROSSMAN, R.B. 1981. Soils and geomorphology in the Basin and Range area of southern New Mexico – Guidebook to the Desert Project. *Memoir New Mexico Bureau of Mining and Mineral Resoures,* **39.**

GUSTAVSON, T.C. 1991. Arid basin depositional systems and paleosols: Fort Hancock and Camp Rice Formations (Plio-Pleistocene), Hueco Bolson, west Texas and adjacent Mexico. *Texas Bureau of Economic Geology Report*, **198**, 49p.

HEAD, M.J. & GIBBARD, P.L. 2005. Early–Middle Pleistocene transitions: an overview and recommendation for the defining boundary. In: Head, M. J. & Gibbard, P.L. (eds.) *Early–Middle Pleistocene Transitions: The Land-Ocean Evidence*. Geological Society of London, Special Publication, **247**, 1-18.

HEREFORD, R. 1993. Entrenchment and widening of the Upper San Pedro River, Arizona. *Geological Society of America Special Paper*, **282**, 46pp.

HILL, C.A., EBERZ, N. & BUECHER, R.H. 2008. A Karst Connection model for Grand Canyon, Arizona, USA. *Geomorphology*, **95**, 316-334.

KELLETAT, D., KOWALCZYK, A., SCHRODER, B. & WINTER, K-P. 1976. A synoptic view on the neotectonic development of the Peloponnesian coastal regions. *Zeitschrift Deutschen Geologischen Gesellschaft*, **127**, 447-465.

KERAUDREN, B. & SOREL, D. 1987. The terraces of Corinth (Greece) – a detailed record of eustatic sea-level variations during the last 500 000 years. *Marine Geology*, **77**, 99-107.

KIRKBY, M. J. 1999. Landscape modelling at regional to continental scales. In: *Process Modelling and Landform Evolution*, Hergarten, S. & Neugebauer, H. J. (eds.), Lecture Notes in Earth Sciences, **78**, 189–203, Springer, Berlin.

KIRKBY, M. J., ABRAHART, R., MCMAHON, M. D., SHAO, J. & THORNES, J. B. 1998. MEDALUS soil erosion models for global change, *Geomorphology*, **24**, 35–49.

KORTMEIER, C.P. 1982. Occurrence of Bishop Ash near Grama, New Mexico. *Geology*, **4**, 22-24.

KOURAMPAS, N. & ROBERTSON, A.H.F 2000. Controls on Plio-Quaternary sedimentation within an active fore-arc region: Messenia peninsula & SW Peloponnese), S. Greece. In: Panayides, I., Xenophontos, C. & Malpas, J. (eds.) *Proceedings of the Third International Conference on the Geology of the Eastern Mediterranean*, 255-285.

LANE, N.F., WATTS, A.B. & FARRANT, A.R. 2008. An analysis of Cotswold topography: insights into the landscape response to denudational isostasy. *Journal of the Geological Society, London*, **165**, 85-103

LEEDER, M.R., MACK, G.H. & SALYARDS, S.L. 1996. Axial-transverse interactions in half-graben: Plio-Pleistocene Palomas Basin, southern Rio Grande Rift, New Mexico, USA. *Basin Research*, **12**, 225-241.

LEEDER, M.R. & STEWART, M. 1996. Fluvial incision and sequence stratigraphy: alluvial responses to relative sea-level fall and their detection in the geological record. In: Hesselbo, S.P. and Parkinson, D.N. (eds.) *Sequence Stratigraphy in British Geology*. Geological Society of London, Special Publication, **103**, 47-61, 1996.

LEEDER, M.R., HARRIS, T. & KIRKBY, M.J. 1998. Sediment supply and climate change: implications for basin stratigraphy. *Basin Research*, **10**, 7-18.

LEEDER, M.R., McNEILL, L.C. COLLIER, R.E.Ll, PORTMAN, C.. ROWE, P.J., ANDREWS, J.E. & GAWTHORPE R.L. 2003. Corinth rift margin uplift: New evidence from Late Quaternary marine shorelines. *Geophysical Research Letters*, **30**, 1611-1614.

LEEDER, M.R., PORTMAN, C., ANDREWS J.E., COLLIER, R.E.Ll, FINCH, E., GAWTHORPE, R.L., McNEILL, L.C., PEREZ-ARLUCEA, M., ROWE, P. 2005. Normal faulting and crustal deformation, Alkyonides Gulf and Perachora peninsula, eastern Gulf of Corinth rift, Greece. *Journal of the Geological Society of London*, **162**, 549-561.

LEEDER, M.R. & MACK, G.H. 2007. Basin-fill incision, Rio Grande and Gulf of Corinth rifts: convergent response to climatic and tectonic drivers. In: *Sedimentary Processes, Environments and Basins: A Tribute to Peter Friend,* Nichols, G., Williams E. & Paola C. (eds.), International Association of Sedimentologists Special Publication **38**, 9-28.

LEEDER, M.R., ANDREWS, J.E., COLLIER, R.E.Ll, GAWTHORPE, R.L., McNEILL, L., PORTMAN, C. & ROWE, P. 2007. *Gulf of Corinth.* Classic Field Geology in Europe, **11**. Terra Publishing, Harpenden.

LEOPOLD, L.B. & BULL, W. B. 1979. Base-level, aggradation, and grade. *Proceedings of the American Philosophical Soc*iety, **123**, 168-202.

LePICHON, X. & ANGELIER, P. 1979. The Hellenic arc and trench system: a key to the neotectonic evolution of the eastern Mediterranean area. *Tectonophysics*, **60**, 1-42.

MACK, G.H., SALYARDS, S.L. & JAMES, W.C. 1993. Magnetostratigraphy of the Plio-Pleistocene Camp Rice and Palomas Formations in the Rio Grande rift of southern New Mexico. *American Journal of Science,* **293**, 49-77.

MACK, G.H., COLE, D.R., JAMES, W.C., GIORDANO, T.H. & SALYARDS, S.L. 1994. Stable oxygen and carbon isotopes of pedogenic carbonate as indicators of Plio-Pleistocene paleoclimate in the southern Rio Grande Rift, south-central New Mexico. *American Journal of Science*, **294**, 621-640.

MACK, G.H., SALYARDS, S.L., MACINTOSH, W.C. & LEEDER, M.R. 1998. Reversal magnetostratigraphy and radioisotope geochronology of the Plio-Pleistocene Camp Rice and Palomas Formations, southern Rio Grande rift. *New Mexico Geological Society Guidebook*, **49**, 229-236.

MACK, G.H. & LEEDER, M.R. 1999. Climatic and tectonic controls on alluvial-fan and axial-fluvial sedimentation in the Plio-Pleistocene Palomas half-graben, southern Rio Grande rift. *Journal of Sed.edimentary Research*, **69**, 635-652.

MACK, G.H., LEEDER, M.R. & SALYARDS, S.L. 2002. Temporal and spatial variability of alluvial-fan and axial-fluvial sedimentation in the Plio-Pleistocene Palomas half graben, southern Rio Grande rift, New Mexico, USA. In: Ashley, G. (ed.), *Sedimentation in Continental Rifts*, SEPM (Society for Sedimentary Geology) Special Publication **73**, 165-177.

MADDY, D. 1997. Uplift-driven valley incision and reiver terrace formation in southern England. *Journal of Quaternary Science*, **12**, 539-545.

MADDY, D. 1998. Reply: Can river terrace flights be used to quantify Quaternary tectonic uplift rates? *Journal of Quaternary Science*, **13**, 574-575.

MADDY, D. & BRIDGLAND, D.R. 2000. Accelerated uplift resulting from Anglian glacioeustatic rebound in the Middle Thames valley, UK? Evidence from the river terrace record. *Quaternary Science Reviews*, **19**, 1581-1588.

MADDY, D., BRIDGLAND, D.R. & GREEN, C.P. 2000. Crustal uplift in southern England: evidence from the river terrace records. *Geomorphology*, **33**, 167-181.

MADDY, D., BRIDGLAND, D.R. & WESTAWAY, R. 2001. Uplift-driven valley incision and climate-controlled river terrace development in the Thames Valley, UK. *Quaternary International*, **79**, 23-36.

MOTTERSHEAD, D.N., GILBERTSON, D.D. & KEEN, D.H. 1987. The raised beaches and shore platforms of Tor Bay: a re-evaluation. *Proceedings of the Geologists Association* **98**, 241-257.

McNEILL, L.C. & COLLIER, R.E.Ll. 2004. Uplift and slip rates of the eastern Eliki fault segment, Gulf of Corinth, Greece, inferred from Holocene and Pleistocene terraces. *Journal of the Geological Society, London*, **161**, 81-92.

PAOLA, C., HELLER, P.L. & ANGEVINE, C.L. 1991. The response distance of river systems to variations in sea level. *Geological Society of America Annual Meeting Absstracts and Program*, A170-A171.

PAOLA, C., HELLER, P.L. & ANGEVINE, C.L. 1992. The large-scale dynamics of grain size variation in alluvial basins. 1. Theory. *Basin Research*, **4**, 73-90.

PAOLA, C. 2000. Quantitative models of sedimentary basin filling. *Sedimentology*, **47**, Supp 1, 1-36.

PARFITT, S.A. & 18 others. 2005. The earliest record of human activity in northern Europe. *Nature*, **438**, 1008-1012

PAVICH, M.J. 1985. Appalachian piedmont morphogenesis: weathering, erosion and cenozoic uplift. In: *Tectonic geomorphology*, Morisawa, M. & Hack, J.T. (eds.), 299-320. Allen and Unwin, Boston.

PAVICH, M.J. 1986. Processes and rates of saprolite production and erosion on a foliated granitic rock of the Virginia Piedmont. In: *Rates of Chemical Weathering of Rocks and Minerals*, Coleman, S.M. & Dethier, D.P. (eds.), 552-590. Academic Press, Orlando.

PEDERSON, J., KARLSTROM, K., SHARP, W. & MCINTOSH, W. 2002. Differential incision of the Grand Canyon related to Quaternary faulting: Constraints from U-series and Ar/Ar dating. *Geology*, **30**, 739-742.

POLYAK, V., HILL, C. & ASMEROM, Y. 2008. Age and evolution of the Grand Canyon revealed by U-Pb dating of watertable-type speleothems. *Science*, **319**, 1377-1380.

POSAMANTIER, H.W. & VAIL, P.R. 1988. Eustatic controls on clastic deposition II. Sequence and systems tract models. In: Wilgus, C.K. Hastings B.S., Kendall, C.G.S.C. Posamentier, H.W., Ross, C.A. & Van Waggoner, J.C. (eds.) *Sea-Level Changes: an Integrated Approach*. Society of Economic Palaeontologists and Mineralogists, Special Publication, **42**, 125-154.

READ, A., GODWIN, M., MILLS, C.A., JUBY, C, LEE, J.R., PALMER, A.P., CANDY, I. & ROSE, J. 2007. Evidence for Middle Pleistocene temperate-climate high sea-level and lowland-scale glaciation, Chapel Hill, Norwich, UK. *Proceedings of the Geologists' Association*, **118**, 143-156.

ROSE, J., CANDY, I., MOORLOCK, B.S.P., WILKINS, H., LEE, J.A., HAMBLIN, R.J.O., RIDING, J.B. & MORIGI, A.N.. 2002. Early and early Middle Pleistocene river, coastal and neotectonic processes, southeast Norfolk, England. *Proceedings of the Geologists Association*, **113**, 47-67.

ROY, M., KELLEY, S., PAZZAGLIA, F., CATHER, S. & HOUSE, M. 2004. Middle tertiary buoyancy modification and its relationship to rock exhumation, cooling, and subsequent extension at the eastern margin of the Colorado Plateau. *Geology*, **32**, 925-928.

SEGER, M. & ALEXANDER, J. 1993. Distribution of Plio-Pleistocene and modern coarse-grained deltas south of the Gulf of Corinth, Greece. In: Marzo, M. & Puigdefabregas, C. (eds.) *Alluvial Sedimentation*. International Association of Sedimentologists, Special Publication, **20**, 37-48.

SACHPAZI, M., CLEMENT, C., LAIGLE, M., HIRN, A. & ROUSSOS, N. 2003. Rift structure, evolution, and earthquakes in the Gulf of Corinth, from reflection seismic images. *Earth and Planetary Science Letters.*, **216**, 243-257.

SHACKLETON, N.J. 1995. New data on the evolution of Pliocene climatic variability. In: Verba, E.S., Denton, G.H., Partridge, T.C., Burckle, L.H. (eds.) *Palaeoclimate and Evolution, with Emphasis on Human Origins*. Yale University Press, New Haven, 242-248.

SMITH, G.A., WANG, Y., CERLING, T.E. & GEISSMAN, J.W. 1993. Comparison of a paleosol-carbonate isotope record to other records of Pliocene-early Pleistocene climate in the western United States. *Geology*, **21**, 691-694.

SOLOMON, J.D. 1932. The glacial succession on the North Norfolk coast. *Proceedings of the Geologists Association*, **43**, 241-271.

STEFATOS, A., PAPATHEODOROU, G., FERENTINOS, G., LEEDER, M. & COLLIER, R. 2002. Seismic reflection imaging of active offshore faults in the Gulf of Corinth: their seismotectonic significance. *Basin Research*, **14**, 487-502.

STUTE, M., CLARK, J.F., SCHLOSSER, P., BROECKER, W.S,. & BONANI, G. 1995. A 30,000 yr continental paleotemperature record derived from noble gases dissolved in groundwater from the San Juan basin, New Mexico. *Quaternary Research*, **43**, 209-220.

SWENSON, J.B. 2005. Fluviodeltaic response to sea level perturbations: amplitude and timing of shoreline translaton and coastal onlap. *Journal of Geophysical Research,* **110**, F03007, doi:10.29/2004JF000208, 2005.

THOMPSON, R.S., WHITLOCK, C., BARTLEIN, P.J., HARRISON, S.P. & SPAULDING, W.G. 1993. Climatic Changes in the Western United States since 18,000 yr B.P. In: H.E. Wright (ed.) *Global Climates since the Last Glacial Maximum*. University of Minnesota Press, 468-513.

TILEY, R., MCKENZIE, D. & WHITE, N. 2003. The elastic thickness of the British Isles. *Journal of the Geological Society, London,* **160**, 499-502.

WATTS, A.B., MCKERROW, S. & FIELDING, E. 2001. Discussion on lithospheric flexure, uplift and landscape evolution of south-central England. *Journal of the Geological Society, London,* **158**, 725-727.

WESTAWAY, R., MADDY, D. & BRIDGLAND, D.R. 2002. Flow in the lower continental crust as a mechanism for the Quaternary uplift of south-east England: constraints from the Thames terrace record. *Quaternary Science Reviews*, **21**, 559-603.

[Manuscript received 29 May 2008; revision accepted 22 July 2008]

THE GLACIAL ERRATIC COLLECTION AT NORWICH CASTLE MUSEUM

P.G. Hoare[1*] *& N.R. Larkin*[2]

[1]School of Geosciences, The University of Sydney, Sydney,
New South Wales 2006, Australia.
[2]The Natural History Department, Norfolk Museums and Archaeology Service,
Norwich Castle Study Centre, Shirehall, Market Avenue, Norwich, NR1 3JQ, UK
* email: pgh@ventifact.co.uk

ABSTRACT

The glacial erratic collection at Norwich Castle Museum & Art Gallery consists of approximately 1600 individual specimens or groups of related erratics. It contains a number of items of considerable geological interest, as well as several collections that were assembled by amateur geologists who were at the forefront of the development of the subject in Norfolk and farther afield. The erratics have been documented in order to produce a MODES database that is not only searchable but may be examined on-line. Unfortunately many of the existing specimens lack detailed information on the circumstances in which they were found, thus greatly diminishing their research potential. Guidelines are provided in the hope that future collecting is carried out more rigorously.

INTRODUCTION

Norwich Castle Museum & Art Gallery (NCM) [**note 1**] holds approximately 1600 individual erratics [**note 2**] or groups of related specimens, these forming a component part of the NCM Geology Collection. The erratic archive consists of more or less geologically exotic material that was transported to East Anglia (Norfolk in particular) and elsewhere by glacial processes.

The glacial erratics, the rest of the geological material and other collections were removed from the NCM in 1999 and 2000 in order to facilitate a major reorganisation of the exhibits and to create new public spaces in the museum. The entire geology collection was transferred initially to warehouses at Fifers Lane near Norwich airport, and then to purpose-built storage facilities (the Superstore) at *Gressenhall Farm and*

Bull. geol. Soc. Norfolk (for 2008) **58**, 37–61.

Workhouse Museum of Norfolk Life near East Dereham in central Norfolk.

Parts of the NCM Geology Collection date back to the early years of the nineteenth century: the strength of this archive is based on material donated by, or purchased from, such well-known figures as W.M. Crowfoot, J. Gunn, C.B. Rose, A.C. Savin and S. Woodward (see Appendix A). This is also largely true for the erratic collection. Subsequently, the erratic archive has expanded as donations were received from members of the public and professional geologists, as a result of fieldwork undertaken by museum staff and, in particular, from the work of the Norfolk Research Committee [**note 3**]. For an insight into the early development of geological collecting in Norfolk, see McWilliams (1974).

Renewed interest in the erratic composition of the oldest glacial sediments in East Anglia has seen the addition of approximately 300 fully documented specimens, principally as a result of fieldwork undertaken scince 2002 by one of us (NRL). This material includes erratics derived from Scandinavian and north British bedrock sources that have been found in the Happisburgh Till and related deposits (see below).

The erratic archive also includes a considerable number of specimens collected from Crag deposits in Norfolk during the past few years. Whilst some of this material has clearly been derived from distant bedrock sources, the East Anglian Crags are generally regarded as belonging to the pre-glacial part of the Quaternary succession. The transport history of these ‘erratics’ is currently under investigation by NRL.

Although the erratic collection was of some importance in terms of its research potential, and a partial, hand-written record had been prepared by the late Paul Whittlesea (see below), it was extremely difficult to make full use of the material. In order to rectify these shortcomings, the authors undertook to document the entire NCM erratic collection and to produce a searchable database that could be examined on-line. This work began in 2004 and has only recently been completed (May 2008).

The purpose of this article is to provide a brief description of the archive and to indicate how records of individual erratics may be accessed over the internet. Since the identity and the ultimate (that is, bedrock) provenance of many of the specimens is uncertain, the status of the database should be regarded as work in progress, and subject to continuing research. The precise nature of many specimens cannot be confirmed until geologists with an intimate knowledge of particular rocks are able to examine them. Sandstones, for example, frequently lack clearly defined characteristics in hand specimen that would otherwise allow them to be linked with particular source outcrops.

THE EARLIEST DONATIONS

The earliest known datable donation of erratics to the NCM was made in 1872 when Rose's widow passed on his geological material (Anon., 1872). Individual specimens and substantial collections of material followed, notably Crowfoot's numerous fossils and erratics acquired in 1918 following his death. Fieldwork by museum staff and by the Norfolk Research Committee, together with donations from members of the public ensured that the archive continued to grow. Brief biographies of some of the more significant early collectors are given at the end of this paper (see appendix A).

Some of the specimens were purchased (either by the donor or the museum, or by both), a strategy that should be regarded with extreme caution under most circumstances as it is impossible to establish the authenticity of the (alleged) find-spot details.

One example will serve to illustrate the practice:

A "[c]abinet of fossils, mostly of local provenance, collector unknown ..." (NWHCM : 1979.119)† may have changed hands several times. It was "... purchased on Norwich market at about the beginning of the [twentieth] century ..." and finally acquired by the Castle Museum from Mr ______, ______, Norwich, in 1979 for £40.00. The cabinet contained two glacially transported fossils, both said to have been found at Corton in Suffolk: *Ostrea* (NWHCM : 1979.119.1383); and an ammonite, recorded as *Sangulata schl.*, in black limestone (NWHCM : 1979.119.1384).

† An explanation of record numbers such as this is given in the section on 'How to access, search and interpret the NCM MODES glacial erratic database' (below).

Such transactions are open to abuse by the alleged discoverer, although 'forgeries' were perhaps more common within the archaeological fraternity (see, for example, White & Plunkett [2004, 16, 35–36]). Note, however, that Rose encouraged quarrymen and brickyard workers who "... soon became acquainted with the ... value of specimens ..." (Woodward, 1893, 388). Savin, too, "... enlisted the services of every longshoreman and beachcomber from Weybourne to Happisburgh ..."; and "... with the help of paid workers he went through the Forest Bed exposures from Overstrand to Beeston ..." (Anon., 1948).

THE CHARACTER OF INDIVIDUAL SPECIMENS

The NCM erratic collection consists largely of bedrock fragments that have been carried by ice sheets to Norfolk and Suffolk. A large proportion of these has been found in and around Norwich and its suburbs, along certain stretches of coast in north and northeast Norfolk, and in parts of the River Waveney valley, especially at Diss, Norfolk, and from Wortwell (Norfolk) to Beccles (Suffolk). This distribution reflects the availability of exposures of glacial and related sediments such as gravel pits, brickyards, river banks and sea cliffs.

Relatively few erratics in the collection are from deposits outside East Anglia, but some of these are of considerable importance. A small, well rounded granite boulder collected at Granite Harbour in McMurdo Sound, Antarctica (NWHCM : 1966.141), caused great excitement when it was rediscovered at the Gressenhall Superstore. This specimen may be a fragment of the underlying bedrock rather than an erratic, but is nonetheless of historical and social interest [**note 4**].

A wide range of igneous, metamorphic and sedimentary rocks is represented, but the archive is dominated by sandstones, limestones, septarian nodules, iron-rich concretions, schists and fossils. Small numbers of particularly far-travelled erratics such as rhomb porphyry and larvikite from outcrops in Oslofjord, Norway, are also present. The erratic fossils include exceedingly well-preserved ammonites, bones of marine reptiles, molluscs and wood. Some of the specimens have been sectioned and polished.

The erratics range in size considerably, but consist mainly of pebbles and small cobbles. The largest specimen is a boulder of rhomb porphyry from Hevingham, Norfolk (TG 183202) measuring 465 x 375 x 295 mm and weighing 75.5 kg (NWHCM : 1955.216) (Fig. 1).

LIMITATIONS OF THE COLLECTION

The erratics of greatest scientific value are those that have been found *in situ* and are accompanied by a comprehensive find-spot record. Unfortunately, many specimens in the NCM collection have been gathered from field surfaces ('field stones') or from beaches; a not inconsiderable number of the erratics are devoid of any information.

Field stones When an erratic has been found on the surface of a field or lying on the floor of a pit or quarry its stratigraphic context is impossible to establish. This is true, for example, for a small fragment of porphyritic rock collected at Keswick, near Norwich (~TG 212049), which bears the inscription "[l]oose in pit" (NWHCM : E977).

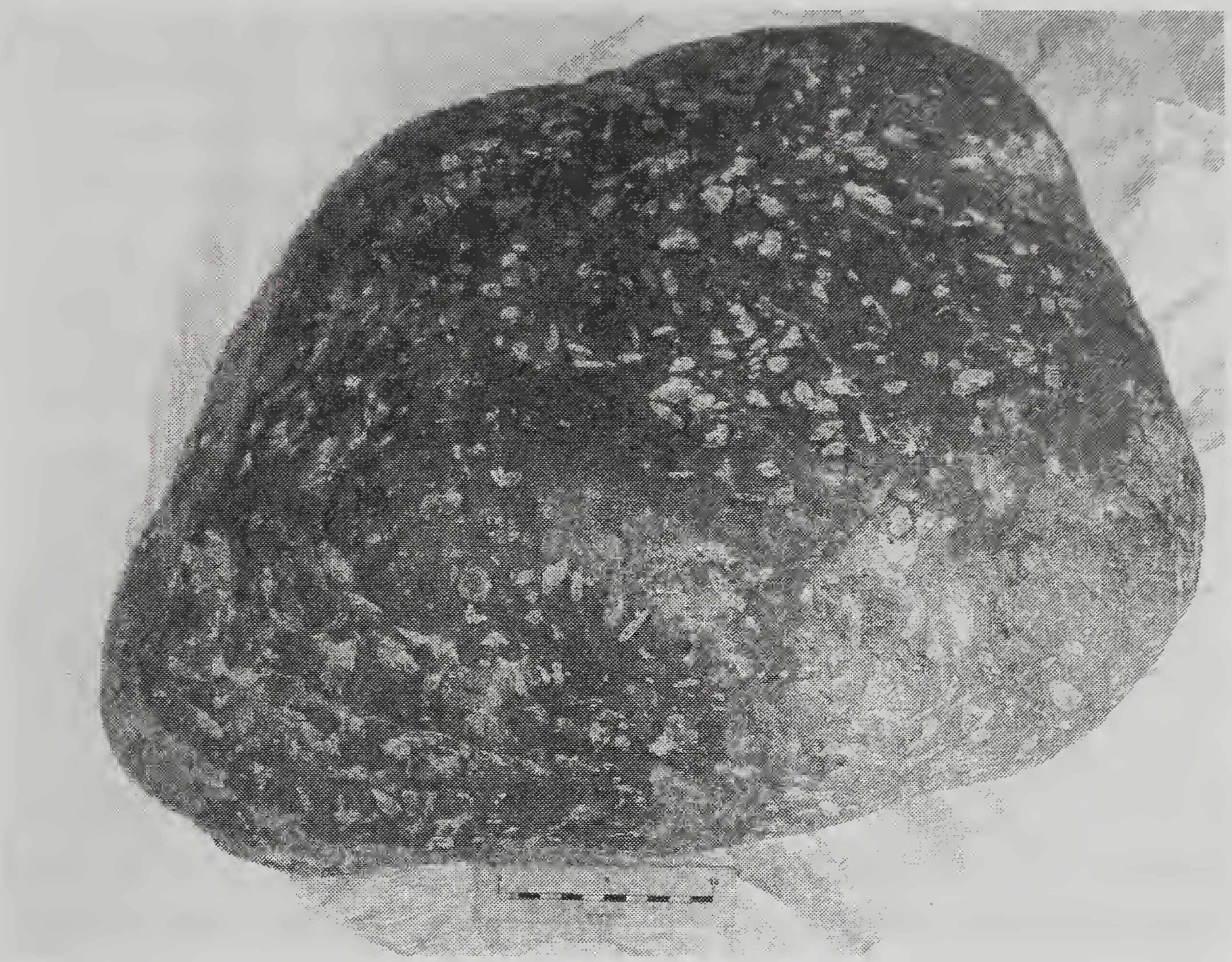


Fig. 1. The largest specimen in the NCM erratic archive: a rhomb porphyry boulder from the Norwich Brickearth at Hevingham (TG 183202), ~12 km north-northwest of Norwich. It measures 465 x 375 x 295 mm and weighs 75.5 kg (NWHCM : 1955.216).

Specimens found on beaches Some of the 'erratics' that have been gathered from beaches, of which there are many in this archive, may have fallen from glacial beds exposed in the adjacent cliffs or been transported along the coast by marine processes.

For many centuries, before sea-water ballast tanks were developed, sand, beach cobbles and other materials were used to ballast vessels. Numerous wrecks litter the coastal waters of eastern England; indeed, Norfolk has the third largest number of shipwrecks of any county in the British Isles (Larn & Larn, 1997). Hughes (1894) described the gradual destruction of a Norwegian vessel, carrying timber from Oslo to Boston, in Lincolnshire, that had run aground off Old Hunstanton in the winter of 1893/4. He warned that its 'Scandinavian ballast' of large boulders of various kinds of gneiss and porphyry may eventually appear among the fallen fragments of a till cliff and

"... be appealed to in proof of its origin" (Hughes, 1894, 6). Certain 'erratics' in the collection may have found their way onto beaches in this manner.

Considerable outcrops of rhomb porphyry and larvikite occur around the shores of Oslofjord. Significantly, a greater proportion of the rhomb porphyry 'erratics' in the NCM archive has been collected from beaches or as field stones than has been found as *in situ* specimens accompanied by well-defined find-spot details.

At Eccles on Sea in Norfolk (TG 4029), pieces of coal have been washed onto the beach from shipwrecked colliers (Pestell & Stannard, 1995, 26). Remarkably, the NCM erratic collection does not contain a single coal specimen, although coal is also found occasionally as an erratic in the Hunstanton Till of late Devensian age which crops out over a limited part of northwest Norfolk (P.G. Hoare, unpublished data).

Increasingly, hardcore and other building material is tipped over cliff faces by local authorities in a bid to 'defend' the coast (or by individuals anxious to dispose of waste without incurring a cost). In addition, very large blocks of larvikite bedrock from Oslofjord, and other exotic rocks, are being employed as rock armour or 'rip rap' at the foot of sea cliffs, in a further attempt to cut down on the rate of coastal retreat. Whilst it is evident that this material has been put in place as part of coastal defensive works, pieces may break off the blocks and become rounded by wave action. Careless collecting of these fragments in the mistaken belief that they represent 'erratics' is a waste of time and may lead to some confusion in the future.

Insufficient geographical details Some specimens acquired many years ago are from locations whose names may occur more than once in a single county and may also be found in two or more counties. There are two Roydon parishes in Norfolk and one in Suffolk, for example. Where neither the county nor the grid reference of the find spot is recorded, such erratics are of greatly diminished value.

Inadequate Stratigraphic Information

Single exposures of Quaternary deposits in East Anglia and elsewhere often reveal a number of superimposed units. Where this is the case, it is imperative that the stratigraphic position of each erratic collected from the section is recorded in detail. When complex stratigraphic sequences are revealed in sea cliffs, the folly of collecting 'erratics' from beaches and making assumptions about their original position in the succession becomes all too clear.

Unfortunately, detailed stratigraphic information is lacking for many of the older

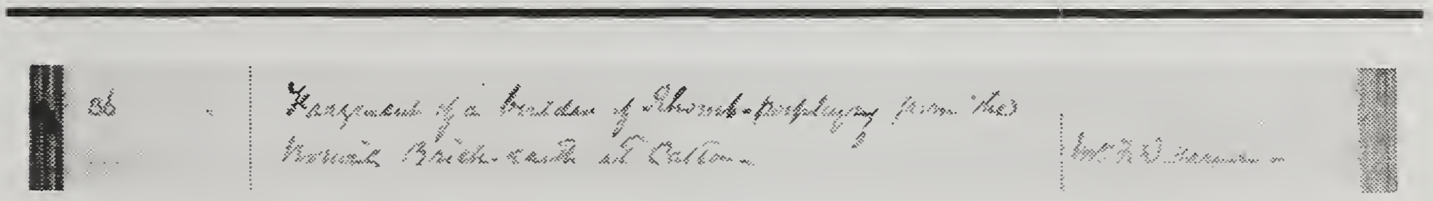
NCM specimens. However, more recent acquisitions are accompanied by a written account of their stratigraphic context. Examples of these include specimens from the Happisburgh Till (the oldest undisputed till in Britain) at Happisburgh (~TG 3831), from the Lowestoft Till at Corton (~TM 5497), and from outwash gravels at Briton's Lane, Beeston Regis, near Sheringham (TG 170414), although it appears that the sequence here is far from straightforward (Pawley *et al.*, 2005, 2006; Banham, 2006). B.M. Funnell (see below) noted the stratigraphic position of the erratics he collected from sites in and around Norwich with meticulous detail.

It is important to acknowledge that certain inadequacies of the older records are due not to carelessness on the part of organisations or individuals but to practices prevailing at the time. Less attention was paid then to details of stratigraphy than is the case today.

SOURCES OF INFORMATION

The NCM Accessions Registers, 1825–present These contain details of (nearly) all the museum's collections and are, without doubt, the most important source of original information on the erratic archive. They list donations and purchases made at the time of receipt at NCM. Each entry includes a unique accession number, a description of the specimen or collection and the name (and sometimes the address) of the donor or vendor (Fig. 2). The Accessions Registers have recently been scanned but, since they contain personal data such as donors' addresses, their use is restricted to museum staff.

The W.M. Crowfoot collection is accompanied by a two-volume catalogue. This is, however, of limited value as the material includes specimens acquired from other individuals with little or no associated information.



36 Fragment of a boulder of Rhomb-porphyry from the Norwich Brick-earth at Catton | Mr F.W. Harmer

Fig. 2. An important record from Norwich Castle Museum's Accessions Register for 1903–1917. It refers to the donation by F.W. Harmer of a rhomb porphyry erratic collected from the Norwich Brickearth at Catton in August 1909 (NWHCM : 1909.36).

It is particularly unfortunate that we have been unable to locate a catalogue of the potentially significant 'West Norfolk Drift' collection made by the Swaffham surgeon and pioneering amateur geologist C.B. Rose; some of his specimens are numbered but the meaning of the numbers is unknown.

Labelled specimens Many specimens have information written directly onto them, or they have labels which are glued to them or are otherwise attached, or they are accompanied by labels which lie loose with them in a bag or in a box. The quality of information on these labels varies greatly, and some ancient labels have deteriorated to such an extent that the writing is partly or wholly illegible.

Publications A handful of the more important and well documented finds have been described in publications (see, for example, Harmer [1904, 309, 314, 1910, 111, 1928, 91 fn 1, 100], Kendall [1904, 236], Hoare & Connell [2005a, b] and Hoare *et al.* [2006a, b]).

The Whittlesea catalogue A hand-written record of the erratic collection was compiled on 21 A3-size sheets of paper by the late Paul Whittlesea in the 1980s. Paul looked at 979 specimens, attached labels E1–E936 and E938–980, recorded their lithology and in some cases noted the name of the collector, the find spot and the NCM accession number. Whilst this was a valuable temporary catalogue for use by museum staff, a significant part of the erratic archive remained unrecorded. In addition, the collection has subsequently grown substantially.

PREPARING THE GLACIAL ERRATIC ARCHIVE DATABASE

During the course of assembling the database, labels that had become detached from specimens during storage were reunited (where the matching of specimen and label could be achieved with confidence); and the opportunity was taken to place individual erratics in separate polythene bags to protect them and to ensure that the label and specimen remained together.

All available sources of information on individual erratics were examined in order to prepare the database. Particular attention was paid to the lithology of the specimen, and to determining if it was found *in situ*. The authors of this note compared identifications recorded in the NCM's Accessions Registers and in the 'Whittlesea catalogue'. Corrections have been made, or doubts expressed, where appropriate. It will be appreciated that further detailed examination of particular erratics will perhaps only be worthwhile when their geographic and stratigraphic details are known with some accuracy.

The information was entered into a Microsoft Excel spreadsheet in the first instance, and these entries were subsequently transformed into MODES records (Fig. 3) [**note 5**]. Each entry can be refined as specimens are examined by specialists with an intimate knowledge of particular rocks and their identity and likely provenance are established. The database will also be extended from time to time as the collection grows.

HOW TO ACCESS, SEARCH AND INTERPRET THE NCM MODES GLACIAL ERRATIC DATABASE

The MODES database software enables a detailed log to be created for each specimen. Every specific sub-heading ('field') is listed in individual cases, but there is rarely sufficient information available to permit an entry against every field (Fig. 3). Since the terminology is specific to the MODES software, some explanation may be helpful.

The record number This is frequently based on the number assigned to a specimen in the Accessions Register. Erratic NWHCM : 1909.36, for example, was the 36th item to be entered in the NCM Accessions Register in 1909 (NWHCM represents the official designation of Norwich Castle Museum). It is actually recorded as 36.09 in the Accessions Register, and some specimens have retained numbers in this original form. Erratics may have been assigned numbers in the collector's catalogue or have been given temporary numbers such as the 'E' numbers in the 'Whittlesea catalogue'; these are noted in a separate field in the MODES record.

Some record numbers have a third set of numerals, e.g. NWHCM : 1956.66.12. The third element is the 'part number'. In this example, there are 12 or more specimens under the principal record number NWHCM : 1956.66. In older records, the figure 12 was placed within parentheses, e.g. NWHCM : 1956.66(12). Funnell assigned parenthetical numbers and letters to much of the material he donated to the museum, but these refer to the site from which the erratic was collected. Thus, (7B) is for Carr's Hills Pit, Costessey (TG 184116) ('A collection of glacial erratics from around Norwich', B.M. Funnell, ~1956, unpublished two-page typescript, Norwich Castle Museum archives).

Each unique record number assigned to an erratic is usually written on the specimen in indelible ink, but some erratics are too small or their surfaces too irregular

Record number	NWHCM : 2005.437
Identification	
Simple name	rock
Other name	erratic
Full name	rhomb porphyry
System	Linnaean
Currency	current
Classified name	
System	Linnaean
Classified name	geology & rock & erratic
System	NMS
Brief description	rock; erratic rhomb porphyry; rock (erratic) *in situ* from the Quaternary (Pleistocene), Happisburgh Till of Happisburgh, Norfolk, England. Collected by NRL, 13.6.2005. Has a few faint striae.
Description	
Form	rock & erratic
Description	
Part:dimen:reading : :	85 x 65 x 50 mm
Field collection	
Method	*in situ*
Person	collector : NRL
Date	13.6.2005
Place	& & Happisburgh & Norfolk & England
Site name	found near to the Happisburgh Forest-bed exposure
Locality type	cliff
Coordinates	NGR: TG 38843 30602
Stratigraphy	age : Quaternary & Pleistocene
Stratigraphy	formation :
Stratigraphy	rock : Happisburgh Till
Acquisition	
Method	staff find
Person	from : Larkin, Nigel
Address	Norfolk Museums & Archaeology Service
Reference number	E
Permanent location	Superstore 2 & 2F/J5/3east & G1814 : 25.5.2006
Recorder	AEA : 4.7.2005
Documentation group	Cited and Figured
Reference	HOARE, P.G., LARKIN, N.R. & CONNELL, E.R. 2006. The first appearance of Norwegian indicator erratics in the glacial succession of northeast Norfolk, eastern England, UK. Quaternary Newsletter, 108, 6-13, Fig. 3.
Notes	found *in situ*
Admin category	default valuation class : B : 1996
Admin category	collection category : 3 : 2001
Admin category	access category : 2 : 2001

Fig. 3. The MODES record for a rhomb porphyry erratic in the NCM archive.

for this to be achieved.

Although most individual records are for a single erratic, some refer to many specimens from the same location. For example, 52 small clasts from the Costessey Brickyard are treated for the time being as one item (NWHCM : 1956.318.100). (Costessey Brickyard was not given a grid reference in Funnell's records; now built over, it was located at ~TG 1711.) The existing part number .100 refers to a sub-section of Funnell's large collection of erratics that he donated to the NCM. If at a later date any of the 52 erratics are described individually, they can be assigned a further part number within the range NWHCM : 1956.318.100.1–1956.318.100.52.

The find spot The site name is typically that of a village, town, sea cliff exposure, pit or quarry that may be of considerable area or length, and is therefore of limited precision. A significant number of specimens have neither the county nor the grid reference of the find spot. The impossibility of resolving the location of erratics that are recorded as coming (say) from Roydon, with no further information, was touched upon under 'Insufficient geographical details' (above).

Co-ordinates In the vast majority of cases, the original record for an erratic is not accompanied by a grid reference. A significant number of finds, however, are described in publications from which the co-ordinates may be extracted (see, for example, Funnell [1954, 1955]). In other examples, the account of the site is sufficiently detailed to allow the co-ordinates to be estimated (see, for example, Hoare & Connell [2005b, fig. 1, 58]).

An acceptable alternative to a grid reference in a MODES record is the 'address' of the find spot composed of up to five sets of information separated by ampersands (the ampersand has a specific terminological function in MODES). An example of this is as follows: Lowry Cole Road 35 & & Sprowston & Norfolk & England (NWHCM : 2008.209). (This specimen was found in the rear garden of 35 Lowry Cole Road and so was probably not *in situ*.) Terms that are equivalent to a house number and street name, the name of a particular field on a farm, for example, might be used where appropriate.

Stratigraphic terminology The Quaternary succession of East Anglia is undergoing substantial revision and there have been calls for the abandonment of older stratigraphic names such as 'Norwich Brickearth' (see, for example, Rose *et al.* [1999, 2, 7] and Lee *et al.* [2004, 49]) and 'North Sea Drift' (see, for example, Hamblin *et al.* [2001, 17, 2005, 83] and Lee *et al.* [2004, 14, 49]). However, we have generally retained in the MODES records those terms that were employed by earlier workers who donated specimens to the collection since to have attempted to replace them at this stage may have led to serious errors.

Photographs Some photographs of individual specimens have been entered into the MODES database, and more will be added as time and other resources allow. Figures 4 to 7 are photographs of four important erratics in the collection.

FUTURE COLLECTING

It will have become apparent that only a minority of the erratics in the present collection is accompanied by more or less complete accounts of their discovery. As a consequence, it is difficult to judge whether many of them were found *in situ*. The majority of the specimens, particularly those within the oldest parts of the collection are, regrettably, of rather limited value.

We therefore urge those who collect erratics in the future not to gather them from beaches, field surfaces or from the floors of pits, but only from *in situ* positions. (Exceptionally, loose specimens might be noted and an attempt made to find identical material in place at the same site.) A comprehensive record of the geographic and stratigraphic setting of the specimen, bearing in mind the following subheadings, will ensure that the full significance of the discovery may be realised.

Date specimen collected: the erratic may be left in place if help is required to remove it and/or to record site details, but remember that some sea cliffs in Norfolk are retreating at an impressive rate!

Site name: for example, Happisburgh lifeboat ramp; East Runton Pillbox; Corton Cliffs; Little Marl Point; Happisburgh Low Light. These names are often reasonably specific but, since they may be duplicated elsewhere, they should be accompanied by a place-name.

Place-name: for example, Woodhill, East Runton, Norfolk, England.

Locality type: for example, brickyard; coastal cliff face; quarry or pit face; river valley bank; temporary utility company (gas, water, electricity) excavation.

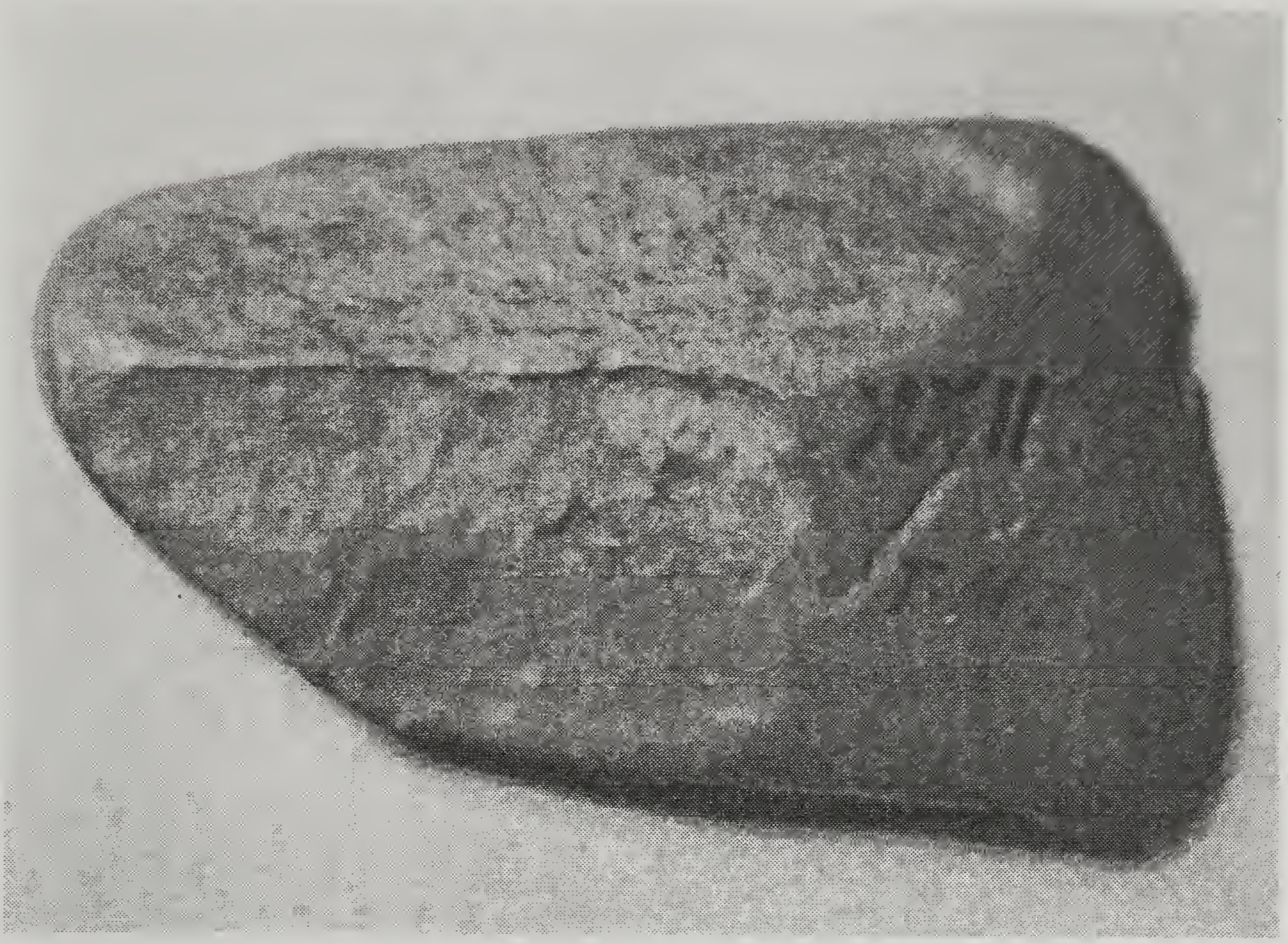


Fig. 4. A greywacke erratic from Two Mile Bottom, Norfolk, near Santon Downham, Suffolk (NWHCM : 1947.33.23.147). The specimen measures 44 x 27 x 6 mm. Few details of the find are recorded, but it is clear that it had lain on the ground surface for some time during which it underwent ventifaction. It now displays a well-developed dreikanter [Ger. = three edges] form. Both the upper and lower surfaces have been polished by wind-borne particles and show a fine vermicular patterning. An extremely sharp keel separates two of the facets shown in the photograph. The third facet exhibits relatively little modification. Ventifaction may have taken place during the Late Devensian when periglacial conditions were responsible for a great reduction in vegetation cover, leading to the accumulation of the Breckland coversands (Bateman, 1995; see also [Hoare *et al.* 2002, 307]). The sands became unstable again in medieval times, due in part to the introduction of rabbits to the area by the Normans. Subsequent overgrazing by sheep may also have played a part. For a vivid account of the movement of sand between Lakenheath Warren and Santon Downham, Suffolk, in the seventeenth century, see Wright (1668). From the Haward Collection.

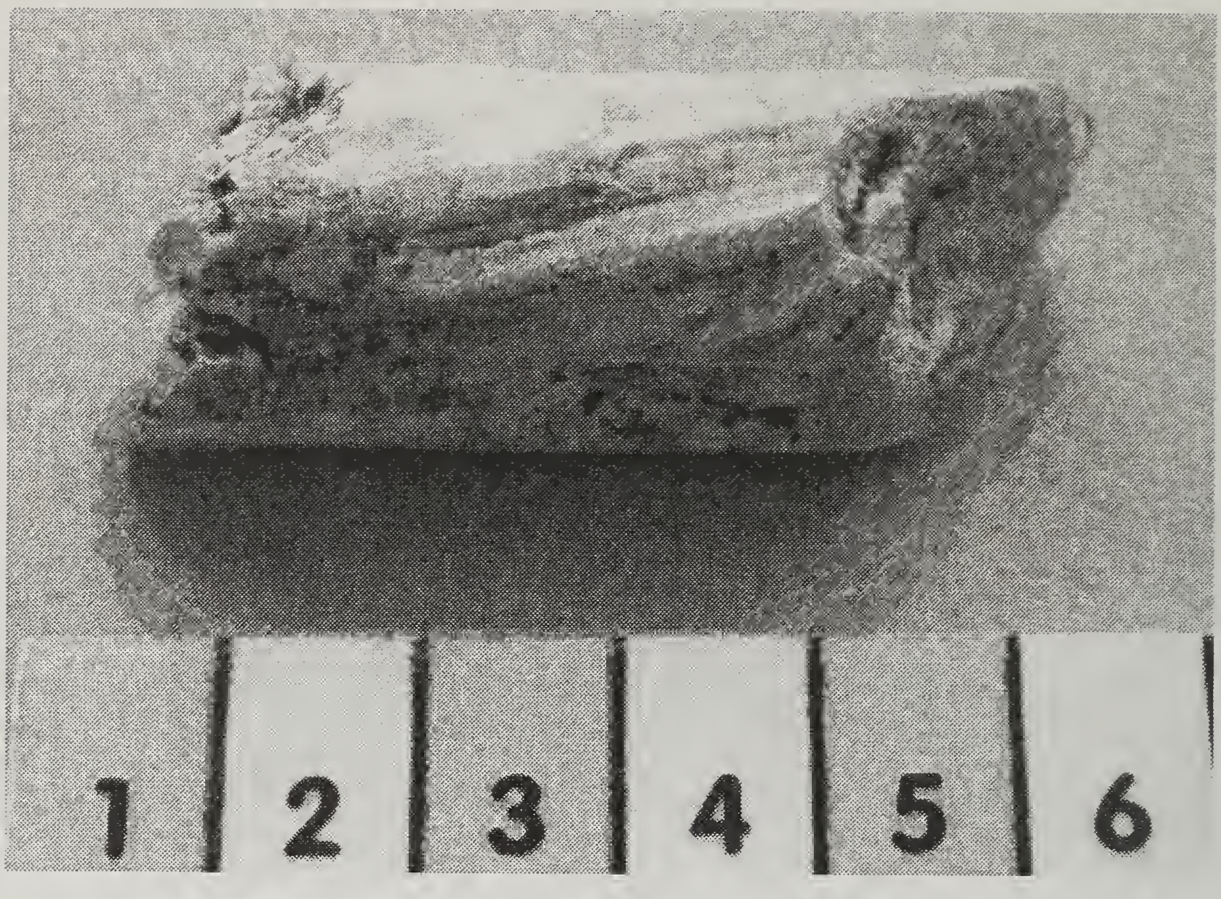


Fig. 5. A rare fossilised fragment of Narwhal tusk (*Monodon monoceros* Linnaeus) from the Norwich Brickearth (North Sea Drift), Sprowston, Norwich (NWHCM : 1886.10). Discovered by Mr George Bacon, and noticed in Woodward (1881, 96) and Newton (1891, 79). Length 64 mm, diameter 19 mm. (See also Anon. [1872].)

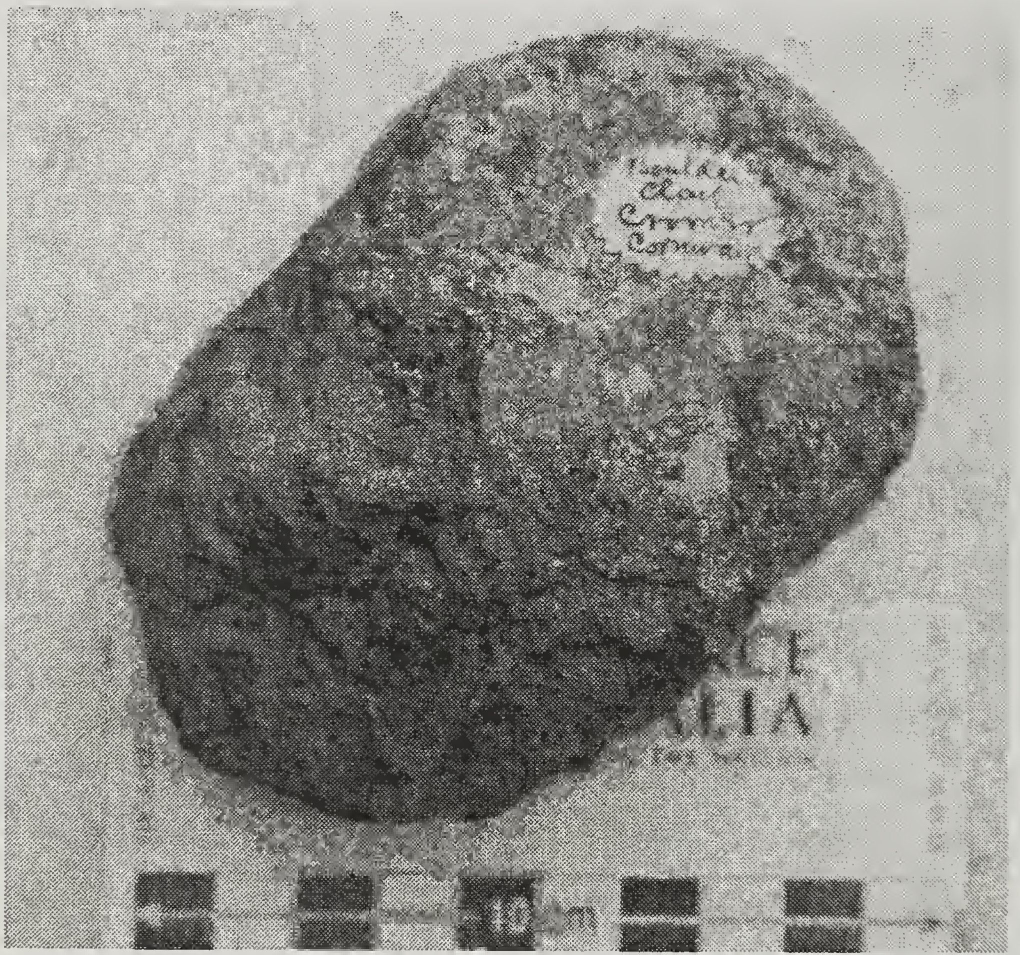


Fig. 6. A larvikite erratic from the Cromer Till (NWHCM : 1935.57.10). Mysteriously, the label reads "Boulder Clay Cromer Cornwall (*sic*)". The specimen was bequeathed by the late F.H. Barclay in 1935 having previously been in the Cox Collection.

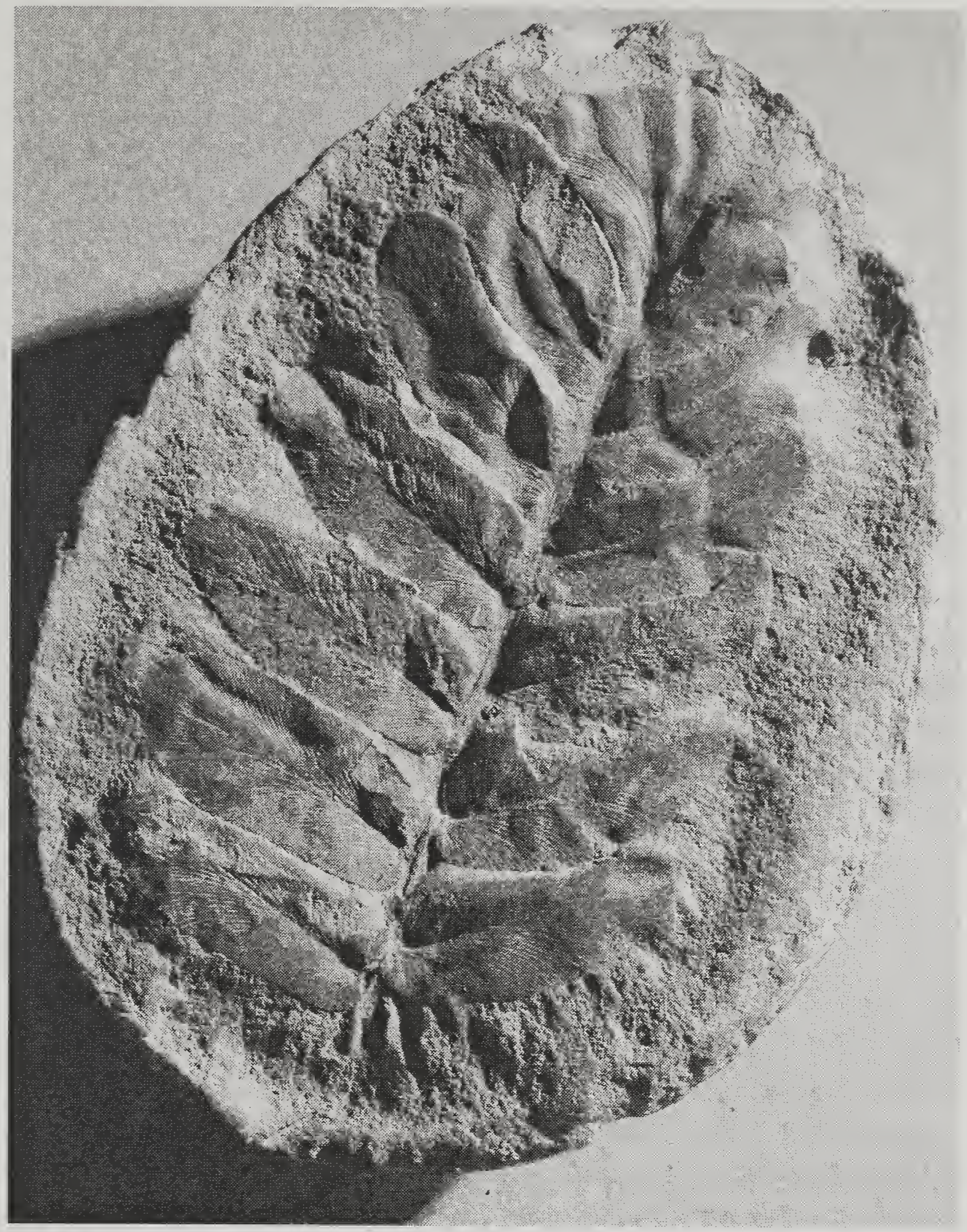


Fig. 7. A beautifully preserved specimen of *Neuropteris gigantea* Sternberg (NWHCM : 2006.1013), an Upper Carboniferous pteridosperm (seed fern) plant, found inside an erratic clast composed of mudstone with slatey cleavage and measuring 90 x 65 x 15 mm in Carbrooke pit, near Watton, Norfolk, by Mr Jim Buck in 2005. The closest source outcrops of Upper Carboniferous bedrock are in the English midlands.

Co-ordinates: a grid reference derived from a large-scale Ordnance Survey sheet or by use of a GPS (global positioning system) receiver; or a MODES-type 'address' (see under 'Co-ordinates' above).

Formation (if known): for example, Hunstanton Till; it is advisable to leave some of the host sediment on the specimen (rather than to clean it thoroughly) in case there is any doubt about the identity of the deposit.

Brief description of the specimen: size, shape, lithology (if known).

Photographs and/or a neat annotated *sketch* of the find spot, including a scale and, if appropriate, a recognisable landmark so that the site may be found again; it may be necessary to revisit the location with a GPS receiver to obtain better co-ordinates, or to remove the specimen.

Labelling: specimens should be labelled as soon as possible in a manner that leaves no room for future confusion; this may be achieved by writing a unique number directly onto them, by gluing or otherwise attaching labels to them or, as an interim measure, by placing them individually in a polythene bag with an accompanying label.

SUMMARY AND FUTURE WORK

The current collection of glacial erratics held by the Norwich Castle Museum & Art Gallery has been built up over a period of approximately 140 years. Many of the specimens were taken from exposures that are no longer open to examination. The archive has now been fully documented with all the available information, and the MODES records, some with digital images, are searchable and browseable on-line, greatly enhancing the usefulness of the collection. It is to be hoped that further work will be undertaken on the existing material so that the identity and ultimate provenance of individual specimens may be established.

Many erratics are accompanied by little or no written information, greatly reducing their research potential. However, some are fully documented and have been employed to resolve uncertainties surrounding the glacial history of East Anglia and farther afield. For example, the number, timing and extent of glaciations in which Scandinavian erratics were introduced to the region has, to some extent, been clarified (Hoare & Connell, 2005a, b; Lee *et al.*, 2005, 49; Hoare *et al.*, 2006a, b).

The erratic collection will surely continue to grow as specimens, accompanied by a full record of the conditions under which they were recovered, are donated to the museum. We hope that the knowledge that such discoveries will be added to the on-line archive and made accessible to all with the minimum of delay will provide an added stimulus.

ACCESSING THE NCM GLACIAL ERRATIC ARCHIVE

To search the collections of Norfolk Museums and Archaeology Service, including Norwich Castle Museum, go to this webpage:
http://www.culturalmodes.norfolk.gov.uk/projects/nmaspub5.asp.

If you require assistance with searching NCM's collections, visit the following webpage:
http://www.museums.norfolk.gov.uk/default.asp?Document=300.01.099x1.

Those who wish to examine the geology collection in the Superstore at the *Gressenhall Farm and Workhouse Museum of Norfolk Life* may make an appointment with the Curator of Geology, Norfolk Museums and Archaeology Service, by telephone (01603-493625) or in writing (The Natural History Department, Norwich Castle Study Centre, Shirehall, Market Avenue, Norwich, Norfolk, NR1 3JQ).

ACKNOWLEDGEMENTS

We are grateful to Dr A.G. Irwin (The Natural History Department, NMAS) for his hospitality, breadth of knowledge and lively conversation; to Mr M.R. Warren (NMAS Collections and Information Manager) for transforming our spreadsheet data to MODES records; to Mr E.R. Connell for his constructive comments on an earlier version of this paper; to Ms F. Ford (NCM Documentation) for assistance with the biographies of some of the donors of erratics; and to Mr D. Simpson (proprietor, 'Simpson's Jet of Whitby') for confirming the identity of jet erratics from Gisleham Brickworks, near Lowestoft, Suffolk.

REFERENCES

ANON. 1872. Norwich Geological Society. *The Norfolk News, Eastern Counties Journal, and Norwich, Yarmouth, and Lyn Commercial Gazette*, **1424** (6 April), 11.

ANON. 1910. *"Citizens of no mean city" Norwich—the East Anglian capital containing brief biographical sketches of a large number of citizens of to-day a special chapter dealing with "notabilities of bygone days" and a brief sketch of "Norwich—Connecticut"*. Jarrold, London, 153 pp.

ANON. 1948. Death of Mr. A.C. Savin. Well-known Norfolk geologist. *Eastern Daily Press* (9 February), 5.

BANHAM, P.H. 2006. The stratigraphy of the Briton's Lane borehole and quarry, Beeston Regis, north-east Norfolk — discussion. *Bulletin of the Geological Society of Norfolk*, **56**, 103.

BATEMAN, M.D. 1995. Thermoluminescence dating of the British coversand deposits. *Quaternary Science Reviews*, **14**, 791–798.

CHERRY-GARRARD, A.G.B. 1965. *The Worst Journey in the World Antarctic 1910–1913*. Chatto & Windus, London, 584 pp.

FUNNELL, B.M. 1954. Notes on some exposures in glacial beds west of Norwich (1954). *Paramoudra Club Bulletin*, **2**, 4–5. (This paper was reprinted in the *Bulletin of the Geological Society of Norfolk* [1988] **38A**.) A single page hand-written ms. and a two-page typescript entitled 'A collection of glacial erratics from around Norwich' [1956.318] by B.M. Funnell are held by the Norwich Castle Museum.

FUNNELL, B.M. 1955. An account of the geology of the Bungay district. *Transactions of the Suffolk Naturalists' Society*, **9**, 115–126. A three page manuscript, largely typed but with hand-written additions and amendments, entitled 'A collection of erratics from the Bungay district' by B.M. Funnell is held by the Norwich Castle Museum.

HAMBLIN, R.J.O., MOORLOCK, B.S.P. & ROSE, J. 2001. A critical assessment of 'A new glacial stratigraphy for eastern England' – a reply. *Quaternary Newsletter*, **94**, 16–18.

HAMBLIN, R.J.O., MOORLOCK, B.S.P., ROSE, J., LEE, J.R., RIDING, J.B., BOOTH, S.J. & PAWLEY, S.M. 2005. Revised pre-Devensian glacial stratigraphy in Norfolk, England, based on mapping and till provenance. *Geologie en Mijnbouw*, **84-2**, 77–85.

HARMER, F.W. 1904. Field excursion to Cromer, Norwich, and Lowestoft. July 9th–14th, 1903. *Proceedings of the Yorkshire Geological and Polytechnic Society*, **15**, 305–314.

HARMER, F.W. 1910. The glacial deposits of Norfolk and Suffolk. *Transactions of the Norfolk and Norwich Naturalists' Society*, **9**, 108–133.

HARMER, F.W. 1928. The distribution of erratics and drift. *Proceedings of the Yorkshire Geological Society*, **21**, 83–150.

HOARE, P.G. & CONNELL, E.R. 2005a. The first appearance of Scandinavian indicators in East Anglia's glacial record. *Bulletin of the Geological Society of Norfolk*, **54**, 3–14.

HOARE, P.G. & CONNELL, E.R. 2005b. The first appearance of Scandinavian indicators in East Anglia's glacial record – reply. *Bulletin of the Geological Society of Norfolk*, **55**, 52–62.

HOARE, P.G., LARKIN, N.R. & CONNELL, E.R. 2006a. The first appearance of Norwegian indicator erratics in the glacial succession of northeast Norfolk, eastern England, UK. *Quaternary Newsletter*, **108**, 6–13.

HOARE, P.G., LARKIN, N.R. & CONNELL, E.R. 2006b. Erratum. 'The first appearance of Norwegian indicator erratics in the glacial succession of northeast Norfolk, eastern England, UK. *Quaternary Newsletter*, 108, 6–13'. *Quaternary Newsletter*, **109**, 21.

HOARE, P.G., STEVENSON, C.R. & GODBY, S.P. 2002. Sand sheets and ventifacts: the legacy of aeolian action in west Norfolk, UK. *Proceedings of the Geologists' Association*, **113**, 310–317.

HUGHES, T.McK. 1894. On some sources of error in the study of drift. *Nature, London*, **50**, 5–6.

KENDALL, P.F. 1904. Erratic blocks of the British Isles. *Report of the seventy-third meeting of the British Association for the Advancement of Science held at Southport in September 1903*, 231–258.

LARN, R. & LARN, B. 1997. *Shipwreck index of the British Isles. Volume 3 – The east coast of England.* Lloyd's Register of Shipping, London, unpaginated.

LEE, J.R., BOOTH, S.J., HAMBLIN, R.J.O., JARROW, A.M., KESSLER, H., MOORLOCK, B.S.P., MORIGI, A.N., PALMER, A., PAWLEY, S.M., RIDING, J.B. & ROSE, J. 2004. A new stratigraphy for the glacial deposits around Lowestoft, Great Yarmouth, North Walsham and Cromer, East Anglia, UK. *Bulletin of the Geological Society of Norfolk*, **53**, 3–60.

LEE, J.R., MOORLOCK, B.S.P., ROSE, J., HAMBLIN, R.J.O., PAWLEY, S.M., RIDING, J.B., JARROW, A.M., BOOTH, S.J., PALMER, A., MORIGI, A.N. & KESSLER, H. 2005. The first appearance of Scandinavian indicators in East Anglia's glacial record – discussion. *Bulletin of the Geological Society of Norfolk*, **55**, 43–51.

McWILLIAMS, B. 1974. The place of early collectors in the development of geological studies in Norfolk. *Bulletin of the Geological Society of Norfolk*, **25**, 3–14.

NEWTON, E.T. 1891. The Vertebrata of the Pliocene deposits of Britain. *Memoir of the Geological Survey of the United Kingdom*. Her Majesty's Stationery Office, London, 137 pp.

PAWLEY, S.M., LEE, J.R., RIDING, J.B., MOORLOCK, B.S.P., HAMBLIN, R.J.O., ROSE, J. & CROFTS, R.G. 2005. The stratigraphy of the Briton's Lane borehole and quarry, Beeston Regis, north-east Norfolk. *Bulletin of the Geological Society of Norfolk*, **55**, 15–41.

PAWLEY, S.M., LEE, J.R., RIDING, J.B., MOORLOCK, B.S.P., HAMBLIN, R.J.O., ROSE, J. & CROFTS, R.G. 2006. The stratigraphy of the Briton's Lane borehole and quarry, Beeston Regis, north-east Norfolk–reply. *Bulletin of the Geological Society of Norfolk*, **56**, 104–105.

PESTELL, R.E. & STANNARD, D.G. 1995. *Eccles-Juxta-Mare a lost village discovered.* Steeple Publishing, Eccles-on-Sea, 86 pp.

ROSE, J., LEE, J.R., MOORLOCK, B.S.P. & HAMBLIN, R.J.O. 1999. The origin of the Norwich Brickearth: micromorphological evidence for pedological alteration of sandy Anglian Till in northeast Norfolk. *Proceedings of the Geologists' Association*, **110**, 1–8.

SUGDEN, D.E. 1994. Erratic. In: Goudie, A.S. (ed.) *The encyclopedic dictionary of physical geography* (2nd ed.), Blackwell, Oxford, p.187

WAKE, T. 1939. Co-ordinating regional research. The Norfolk Research Committee. *East Anglian Magazine* (January), 5 pp.

WELLS, C. 1969. Untitled. *Norfolk Research Committee Bulletin*, **18**, 2–3.

WHITE, M.J. & PLUNKETT, S.J. 2004. *Miss Layard excavates: a Palaeolithic site at Foxall Road, Ipswich, 1903–1905.* Western Academic & Specialist Press, Liverpool, 196 pp.

WOODWARD, H.B. 1881. The geology of the country around Norwich. (Explanation of quarter sheets 66 N.E. and 66 S.E. of the one-inch geological survey map of England and Wales.) *Memoir of the Geological Survey. England and Wales*. Her Majesty's Stationery Office, London, 215 pp.

WOODWARD, H.B. 1893. A memoir of Caleb B. Rose, F.R.C.S., F.G.S. *Transactions of the Norfolk and Norwich Naturalists' Society*, **5**, 387–403.

WRIGHT, T. 1668. A curious and exact relation of a sand-floud [flood], which has lately overwhelmed a great tract of land in the county of Suffolk; together with an account of the check in part given to it; communicated in an obliging letter to the publisher, by that worthy gentleman Thomas Wright Esquire, living upon the place, and a sufferer by that deluge. *Philosophical Transactions of the Royal Society of London*, **3**, 722–725.

[Manuscript received 14 May 2008; revision accepted 3 June 2008]

NOTES

Note 1. The Norfolk & Norwich Museum was established in 1825 in a building in the Haymarket, Norwich. It moved to purpose-built accommodation in what is now Jarrold's office equipment premises in Exchange Street in 1833. From 1838 until 1894 it was housed in a property in St Andrew's Street, now the site of St Andrew's multi-storey car park. The Norfolk & Norwich Museum was taken over by Norwich Corporation in 1894 and the collection was transferred to the Norwich Castle in that year.

Note 2. An erratic is "[a] rock or boulder that has been carried to its present location by the action of a glacier" (Sugden, 1994). There is no reason to regard them as especially large or particularly exotic compared with the bedrock they now overlie. Although erratics are found in association with glacial and related sediments, there is a considerable likelihood that some of those in East Anglia may first have been transported from central England by pre-glacial, Early and early Middle Pleistocene river systems such as the Ancaster, Bytham and proto-Thames; these rivers may also have been responsible for much of the far-travelled material in the 'pre-glacial' East Anglian Crags (see above). Since many erratics are composed of durable lithologies, they are also likely to have been reworked from one sediment into another and to have been transported within a variety of different environments.

Note 3. At an informal meeting held at Norwich Castle Museum on 29 June 1934 it was decided to form a Norfolk Research Committee. The meeting was attended by delegates representing the Norfolk and Norwich Archaeological Society, the Norfolk and Norwich Naturalists' Society, the Prehistoric Society of East Anglia, the county branches of the Geographical and Historical Associations, the Norfolk and Norwich Aero Club, the Norwich Science Gossip Club, Norwich Castle Museum and Thetford Corporation Museum (extract from letter dated 30 July 1934, Minute book, 1934–1959). It was in no sense a new society, rather a co-ordinating organisation. For a description of the Committee's work, see Wake (1939). For a somewhat more irreverent account of their ambitions, see Wells (1969).

Note 4. The granite boulder was brought to England by Lieutenant Commander H.E. de P. Rennick. Henry Rennick was on board the *Terra Nova* under the command of Captain E.R.G.R. Evans when she returned to the Antarctic on 18 January 1913 to discover that Captain R.F. Scott's polar party had perished in March 1912 within 18–19 km of safety (Cherry-Garrard, 1965, 480, 565). On 22 January 1913 the *Terra Nova* began its journey back to the U.K., coasting up the Western Mountains to Granite Harbour where Tryggve Gran went off to pick up a depot of geological specimens (Cherry-Garrard, 1965, 567). It is possible that the granite boulder was collected on that occasion. It is now on display in the exhibition 'To The Ends of The Earth: Norfolk's Place in Polar Exploration' at Norwich Castle Museum & Art Gallery. For more information on this exhibition, visit http://www.museums.norfolk.gov.uk/polar/.

Note 5. MODES (Museum Object Data Entry System) is the most widely used cataloguing system in British museums (it is employed by more than 330 museums and archives, of all types and sizes). The data structure is based on national standards, the retrieval of information is by index or free text searching and it has built-in links to images, texts and other multimedia resources with public access web server applications able to deliver records over the internet to clients using a standard web browser. General information on MODES may be found at http://www.modes.org.uk/.

APPENDIX A

PRINCIPAL COLLECTORS AND DONORS: SOME BIOGRAPHICAL NOTES

This section has been largely compiled from obituaries and from Anon. (1910). It is hoped that it will eventually be expanded into a rather more detailed account of those who were influential in the development of geology in Norfolk.

Barclay, Francis Herbert (1870–28 January 1935). A member of the well-known banking family, he donated his collection to the NCM in 1935. Obituary: *Transactions of the Norfolk and Norwich Naturalists' Society* (1936) **14**, 109.

Brydone, Reginald Marr (1873–6 August 1943). A solicitor, he was principally concerned with the geology of the Chalk. Obituary: *Transactions of the Norfolk and Norwich Naturalists' Society* (1944) **15**, 444–445.

Cambridge, Philip C. (2 June 1918–29 May 1993). On leaving the R.A.F. he was appointed Chief Technician and research assistant in the School of Environmental Sciences at the University of East Anglia where he stayed for 15 years. Obituary: *Journal of Conchology* (1994) **35**, 83–86.

Crowfoot, William Miller, M.B., F.R.C.S. (Eng.), L.S.A., J.P. (1868–1918). A physician and surgeon practising in Beccles, Suffolk.

Dixon Hewitt, H. (1878–1966). Honorary curator of the Ancient House Museum, Thetford, in the 1920s and 1930s. He collected widely in the Breckland area. The NCM has a considerable archive of correspondence between Dixon Hewitt and his notable contemporaries.

Ellis, Edward Augustine, D.Sc. (*h.c.*), F.L.S. (1909–22 July 1986). Keeper of Natural History at the Castle Museum, Norwich (1928–1956); Secretary (1959–1963) and President (1979–1983) of the Norfolk Naturalists' Trust; Honorary Vice-President of the Norfolk Research Committee (1978). "... a writer and broadcaster of felicity, a communicator of something approaching genius, and a man held secure in a rare public affection" (*Eastern Daily Press* 23 July 1986, 10). See also *Eastern Daily Press* 5

February 1983, 3; 23 July 1986, 1; 25 July 1986, 9; 29 July 1986, 3; 1 September 1986, 3; 19 September 1986, 21; and 1 November 1986, 3.

Funnell, Brian Michael (1933–2000). A Quaternary micropalaeontologist of world renown, he was one of the founding professors of the School of Environmental Sciences at the University of East Anglia. Probably the most significant individual contributor to the erratic collection, particularly during the early part of his academic life. Obituary: *Quaternary Newsletter* (2000) **92**, 2–20. See also Vine, F.J. 2000. Professor Brian Michael Funnell M.A., Ph.D., F.G.S. Tribute given at Funeral and Service of Thanksgiving, 11 May, 2000. In Dixon, R.G. (ed.) *The Geological Society of Norfolk 50th Anniverary Jubilee Volume*, 4–6.

Harmer, Frederic William, M.A., F.G.S. (24 April 1835–11 April 1923). A Norwich-based clothing manufacturer; Mayor of Norwich 1887–1888. Best known for his study, with Searles V. Wood, Jr of the Crag mollusca. During 1864–1872 he carried out with Wood the first geological survey of East Anglia. Obituary: *Transactions of the Norfolk and Norwich Naturalists' Society* (1923) **11**, 477–483.

Rose, Caleb Burrell, F.R.C.S., F.G.S. (10 February 1790–29 January 1872). He studied medicine at Guy's and St Thomas's hospitals, London, although "[t]here is no record of his passing any examinations ..." (Woodward, 1893, 387); he subsequently practised as a surgeon in Swaffham for 43 years. He was a prodigious collector, principally from the Middle and Lower Chalk and the 'brickearth' of west Norfolk (Woodward, 1893, 389). Obituary: Woodward (1893) (see references).

Sainty, James Edward, M.M., B.Sc. (1882–6 June 1967). Born at Hingham, Norfolk, a science teacher at the City of Norwich School for more than 40 years, he lived at West Runton at the end of his life. President's Address to the Norfolk and Norwich Naturalists' Society, 1951: Sainty, J.E. 1952. The geology of Norfolk. With special reference to the Pleistocene period. *Transactions of the Norfolk and Norwich Naturalists' Society*, **17**, 149–185. Obituaries: *Eastern Evening News* 7 June 1967, 22; *Norfolk Archaeology* (1969) **34**, 336.

Savin, Alfred Collison (?1861–1948). A Cromer shopkeeper whose premises in Church Street were frequented by Sir John Evans, Faulkner, Prestwick, Abbé Breuil, Fairfield Osborne and James Reid Moir. The windows of his little shop were "... filled with elephant teeth, amber and silver ware ..." (*Eastern Daily Press* 9 February 1948, 5). The coarse gravel capping the cliffs at West Runton had in 1878 yielded a hand axe to a Cromer schoolboy, A.C. Savin (Sainty, 1952, 152 [see under Sainty, above]). His main interests were said to be amber and mammalian fossils. He collected Forest Bed fossils from the 1880s until the 1940s; most of his specimens were purchased by the Natural History Museum, South Kensington. See Savin, A.C. 1950. *Cromer in the county of Norfolk. A modern history by the late Alfred Collison Savin*, revised 1st edition, Rounce & Wortley, Holt, 144 pp. Obituary: *Eastern Daily Press* 9 February 1948, 5.

Whittlesea, Paul S. (1957–2007). An 'amateur' geologist who maintained the highest professional standards, he developed an international reputation for his work on Chalk bryozoa. He was also responsible for the not inconsiderable task of preparing the 'Whittlesea catalogue', a hand-written record of the Castle Museum, Norwich, erratic collection, in the 1980s. Obituary: *Bulletin of the Geological Society of Norfolk* (2007) 57, 3-6.

BACK ISSUES OF THE BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK AND 50th JUBILEE VOLUME

The Geological Society of Norfolk (GSN) has back issues of the Bulletin available for purchase as outlined below. The Bulletin may not be easily available at some institutions - except through Inter-Library Loan – so individuals might consider a recommendation for purchase by institution libraries.

At present we can supply all issues except volumes 19, 32 and 42. Volumes 23, 27 and 28 are in short supply (less than 10 remaining). Volumes 1-10 and 11-18 are only available as reprint volumes 38A and 39A.

There are plenty of copies of the now famous 'East Anglian Geology' issue, volume 34.

Back issues of the Bulletin are available at £3-50 per issue to GSN members and £10-00 per issue to non-members. For purchase of two or more issues it is cheaper for non-members to join the society (£10-00 per year) and buy at member price.

In addition, the society published a special Jubilee volume (edited by Roger Dixon) to commemorate its 50th anniversary. This volume is dedicated to Prof. Brian Funnell and contains a number of articles about Prof. Funnell, his research and the early days of the Society. The Jubilee Volume is free to GSN members. The remainder are available at cost (£8-50).

If you would like to place an order please discuss your requirements with Julian Andrews at UEA, preferably on the following e-mail address: j.andrews@uea.ac.uk

Or by post to: Prof. Julian Andrews, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ.

CLAY MINERALOGY OF CROMER FOREST BED FORMATION SEDIMENTS, WEST RUNTON, NORFOLK

S. Brough and J.E. Andrews

School of Environmental Sciences,
University of East Anglia,
Norwich, NR4 7TJ, UK

ABSTRACT

The clay mineralogy of Cromer Forest-bed Formation sediments at West Runton, Norfolk is characterised by; 1) low kaolinite abundance, typically <10%; 2) illite abundance typically in the range 38-66%; and 3), smectite present in all samples (25-90%), either interstratified with illite, or as a discrete mineral. Smectite is most abundant (47-90%) in samples from the freshwater bed (WRFWB) and in the basal Mundesley Member. Smectite clays in the Cromer Forest-bed Formation sediments as a whole are interpreted as mainly detritally sourced. Greater than 50% smectite content in the WRFWB is likely to be from detrital sources or from the early diagenesis of illitc clays in marshy waterlogged sediments. However, a small amount of volcanogenic smectite in the WRFWB cannot be ruled out since a volcanic mineral assemblage has recently been described from the 20-120 µm size fraction (Brough et al. in press).

INTRODUCTION

In the mid 1990s, as part of a study of the diagenesis of the Middle Pleistocene West Runton Freshwater Bed (bed f of West 1980, and hereafter WRFWB), Hannam *et al.* (1996) raised the possibility that smectite clays in the bed might come from a volcanic source. As there was no known local Middle Pleistocene volcanism in the region a far-field source was discussed and the Eifel region of Germany identified as a possible source. As Hannam *et al.* (1996) based their suggestions on just two clay mineralogy samples, one from the central part of the WRFWB and one from the upper altered part (their 'oxidised Fe bed'), the present study was designed to follow up and extend the clay mineralogical study: in particular to confirm (or otherwise) a smectite-dominated mineralogy for the whole WRFWB deposit, but also to test whether the

---

Bull. geol. Soc. Norfolk (for 2008) **58**, 63–78.

under- and over-lying stratigraphic horizons of the Cromer Forest-bed Formation were similarly smectite-dominated.

The clay mineralogy of most sedimentary deposits reflects weathering of parent materials and the subsequent conditions of *in situ* clay formation or modification (Weaver, 1989; Brady and Weil 2002). The clay mineralogy of most temperate siliciclastic mudrocks is dominated by illitic detrital clays inherited from weathering of crustal materials. For example, the clay mineralogy of Holocene sediments in the Wash-Fenland embayment of East Anglia is dominated by inherited illitic clays, with subordinate kaolinite and expandable clays (Brew *et al.*, 2000). The identification of a geologically young sedimentary unit dominated by smectitic clay is thus quite unusual and deserves scrutiny, particularly if the smectite has potential origins from the weathering of volcanic ash or dust.

While many smectites are formed by the weathering of volcanic glass, rich in Si, Al, Ca, Na and K (Weaver 1989), the presence of smectite is not diagnostic of a volcanic ash precursor. Some smectites are simply detrital, inherited from the argillisation of micas, feldspars, iron and magnesium rich minerals (Weaver 1989), or formed *in situ* by weathering of detrital clays and other silicates under waterlogged conditions where base cation removal is slow (e.g. see Brady and Weil 2002; Andrews *et al.*, 2004). One way to help establish the source of smectite is to examine its X ray diffraction (XRD) response to potassium (K^+) saturation (Weaver 1958), a technique used in this study.

SITE DESCRIPTION, STRATIGRAPHY AND PALAEOENVIRONMENTS

The study site is located at the base of the coastal cliffs at West Runton, north Norfolk, to the east of Woman Hythe (West Runton Gap) between grid references TG 186431 and TG 18943 (Fig. 1). The West Runton Freshwater Bed (WRFWB; bed f of West 1980) is part of the Cromer Forest-bed Formation and the type site of the Cromerian Stage interglacial period. The Cromer Forest-bed Formation is a mixed shallow marine and fluvial siliciclastic sediment package (Fig. 2) that rests unconformably on the Upper Cretaceous chalk surface and beneath the Anglian glacial sediments (Runton Till Member of Lee *et al.*, (2004) formerly the Third Cromer Till of Banham (1968)). The sediments below the WRFWB are only intermittently exposed, but comprise shelly estuarine and fluvial gravels, sands and silts of Pre-Pastonian, Pastonian and Beestonian age (parts of the Runton, Paston and Sheringham Members of West (1980)). The deposits above the WRFWB are dominated by marine transgressive tidal sands (Mundesley Member; West 1980) and then freshwater sands and silts of the Bacton Member (West 1980).

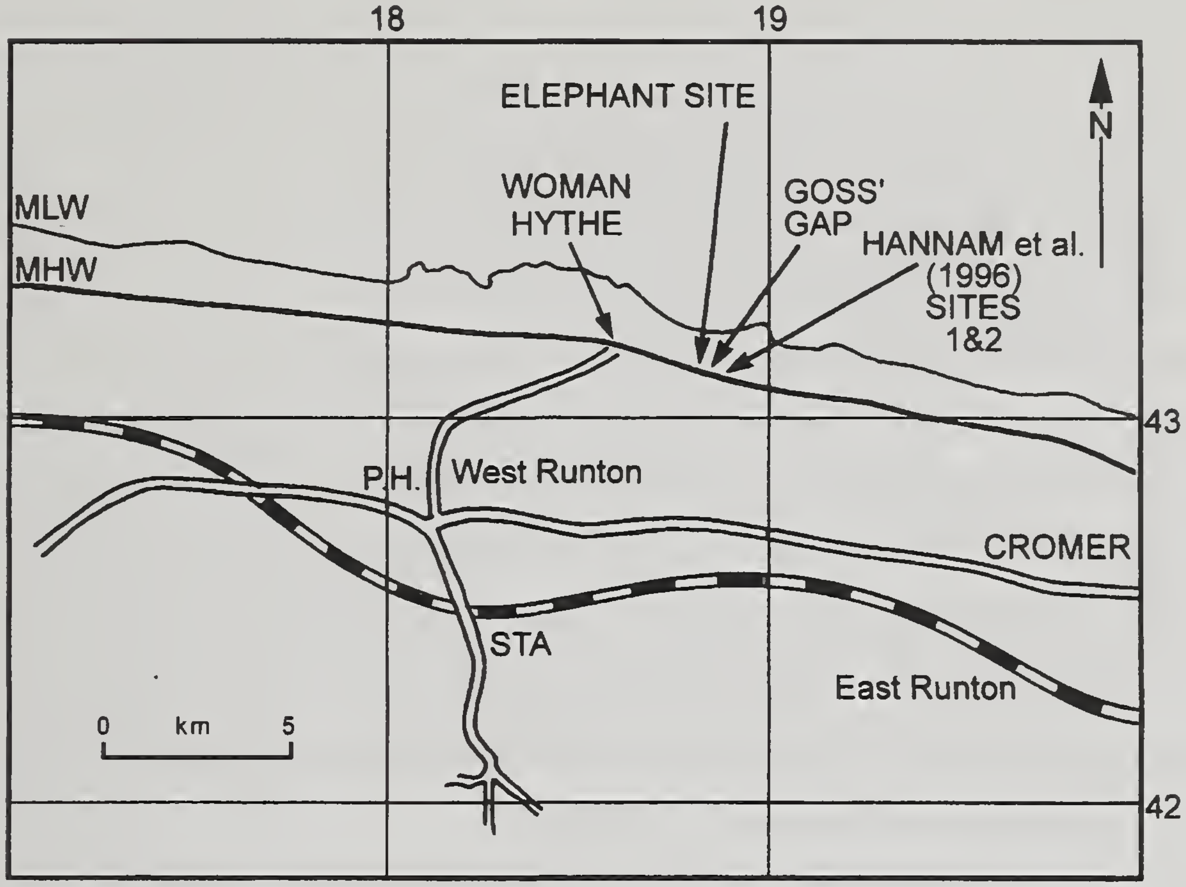


Fig. 1. Location map showing sample site in this study and related localities of Stuart (1991) and Hannam *et al.*, (1996). Grid lines are from the Ordnance Survey map.

The WRFWB itself is a dark coloured, organic-rich (4-10 wt% organic carbon; Hannam *et al.* 1996) unit of muddy silts and sands. A full description is not made here as detailed descriptions are available in West (1980) and Gibbard *et al.* (in press); however, it is worth noting that the bed contains abundant pebbles of flint and indurated silt, woody detritus and freshwater bivalves and gastropods, particularly in its lower half. The deposits represent fine-grained silt deposition in fluvial channel and pool environments (West 1980), punctuated by flood events that fed coarser detritus into depressions (Gibbard *et al.* in press). The high organic matter contents and palynology suggest a wooded river valley environment, with herbaceous vegetation and abundant submerged aquatic vegetation (West 1980; Stuart 1975; Gibbard *et al.*, in press).

The upper 15-20 cm of the WRFWB are paler grey, but with prominent iron oxide staining: the sediments here have been decalcified and organic matter and depositional sulphides have been oxidised by early diagenetic reactions that most likely occurred due to post-depositional groundwater flow (Hannam *et al.* 1996; Bottrell *et al.*, 1998; Gibbard *et al.*, in press). Earlier suggestions that this 'oxidised Fe bed' represented a palaeosol (West 1980; Stuart 1991) have not been substantiated by positive evidence (see discussion in Gibbard *et al.*, in press).

SAMPLING SCHEME AND METHODS

Details of the sample positions are shown on Figure 2 and detailed in Table 1. In brief, 8 spot samples were taken through a vertical profile of the WRFWB at a site ~10 m west of the western wall of the elephant excavation site (Stuart, 1991) and approximately 100 m west of the sample site of (Hannam *et al.*, 1996). Earlier work has demonstrated that diagenetic alteration of molluscan aragonite, organic carbon and pyrite sulphur has been minimal in the lower 50 cm of the deposit (Hannam *et al.*, 1996; Bottrell *et al.*, 1998) and on this basis we expected samples 1, 3, 4, 5 and 14 (see below and Table 1) to be best preserved from burial diagenetic alteration. Samples 8 and 9 (Table 1) came from the oxidised Fe bed (see above). Sample 14 was taken ~20 m west of the main section, where the oxidised Fe bed is clearly much thinner and the upper part of the WRFWB is fossiliferous and apparently not altered.

Samples were also taken from clay/silt units in the Cromer Forest-bed Formation sediments above and below the WRFWB. Sample 2 (Table 1) came from laminated clays and sands 30 cm below the base of the WRFWB (bed d of West 1980). Samples 10 and 11 were taken from grey clay laminae in marine tidal sand units of the Mundesley Member (West 1980), sample 10 from the base of a bed directly overlying the basal 'Monkey Gravel' or *Leda Myalis* Bed (Preece & Parfitt 2000), which lies on the upper surface of the WRFWB. Sample 12 was from silty claystones in the freshwater silts of the Bacton Member (West 1980). Sample 13 (Table 1) came from the base of the Runton Till overlying the Cromer Forest-bed Formation sediments.

For comparison and control, the Cromer Forest-bed Formation samples were augmented by: 1) a sample of modern saltmarsh silty clays from Stiffkey on the north Norfolk coast (sample 15 Table 1), chosen as representative of modern 'North Sea' clay sedimentation from detrital sources; and 2), laboratory grade bentonite clay (sample 16 Table 1), to act as a control for the K^+ saturation experiments (see below)

Laboratory methods

In preparation for clay mineral identification by XRD, organic matter was oxidised with cold 30% hydrogen peroxide overnight, followed by boiling on a steam bath for 3-4 hours. $CaCO_3$ was removed by a gentle sodium acetate/acetic acid leach. However, in most of the

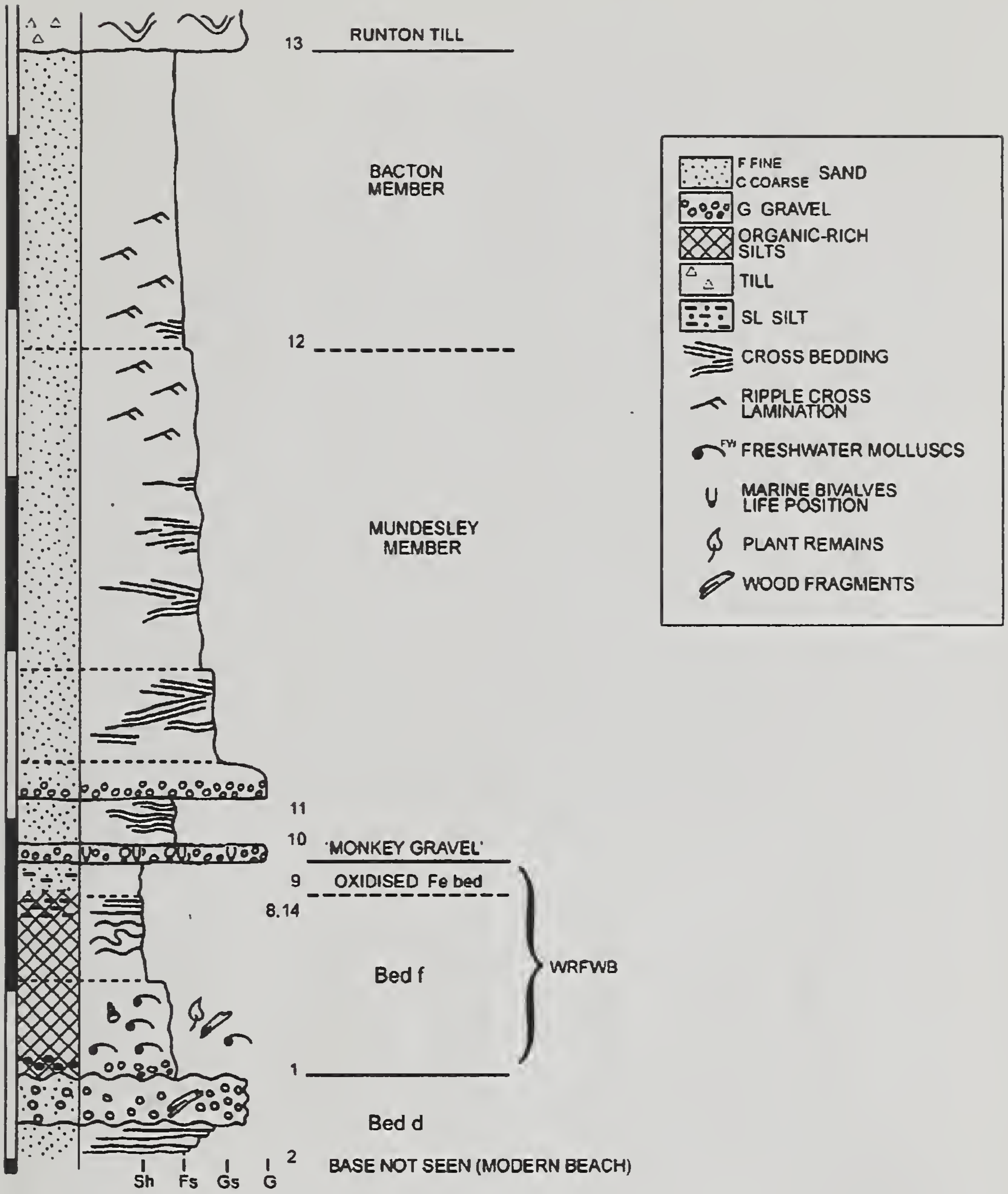


Fig. 2. Summary stratigraphy and sedimentary log of the studied cliff section at West Runton as seen in June 2005. Positions of samples 1-13 are marked. Beds d and f of the WRFWB, Mundesley and Bacton Members are after West (1980). Runton Till Member after Lee *et al.*, (2004).

Table 1. Details of field sampling and stratigraphic horizons studied.

Sample No.	Height above base WRFWB (0 cm = base bed f)	Stratigraphic unit	Sediment Descriptions
13	+ 600	Runton Till	Coarse sands, silt, clay and sub-angular flint pebbles (2-3 cm), diamicton, poorly-sorted. Chalk pebbles <2 mm. Colour: very pale brown 10YR 7/4
12	+ 400	Bacton Member	Fine sands and sub angular flint pebbles (2-3 mm), poorly sorted, no fossils. Colour: pale yellow 5Y 8/3
11	+185	Mundesley Member laminated clays	Coarse sands and silty units, poorly-sorted, sub-angular grains; prominent iron oxide staining, ? poorly-preserved fossils (<1 mm). Silty units are darker: Colour: pale brown 10YR 6/5; Sands colour: yellow 10YR 8/8
10	+145	Mundesley Member clay unit, immediately above 'Monkey Gravel'	Coarse sands and silty units, poorly-sorted; silts and clays laminated in places with coarse sandy intercalations. Silts/clays colour: very pale brown 10YR 7/4. Sands colour: yellow 10YR 7/8
9	+128	WRFWB (bed f) top of oxidised Fe bed	Very fine sands and silts, well-sorted, fissile, red iron stained areas and yellow elemental S staining. No fossils. Colour: greyish-brown 10YR 5/2
8	+106	WRFWB (bed f) base of oxidised Fe bed	Fine sands and silts. Colour: brown, 10YR 5/3
7	+ 83	WRFWB (bed f)	Very fine sand and silts, well-sorted, no fossils. Colour: dark brown 10YR 3/3

14*	~ + 97	WRFWB (bed f)	Very fine sands and silts, well-sorted, fragmentary fossils <3 mm, with darker organic matter-rich aggregates. Colour: dark grey 10YR 4/1
6	+67	WRFWB (bed f)	Very fine sands and silts, well-sorted, a few very small fossil fragments < 1 mm. Colour: very dark greyish-brown 10YR 3/2
5	+53	WRFWB (bed f)	Medium/fine silts, well-sorted, some fossil fragments <2 mm. Colour: 10YR 3/3 dark Brown
4	+41	WRFWB (bed f)	Fine silt, well-sorted, occasional sub angular flint pebbles ~5 cm, indurated silt/clay clasts, whole bivalves up to 4 mm, plus fragments. Colour: dark brown, 10YR 3/3
3	+ 27	WRFWB (bed f)	Fine silt, well-sorted, occasional pebbles (0.5cm), whole and fragmentary bivalves and gastropods, mostly 3 mm - <1 mm. Occasional thin bivalve shells >10mm. Colour: dark yellow brown, 10YR 4/4
1	+ 2	WRFWB (bed f) base	Very fine sands and silt, moderate-sorting, sub-angular sands, larger irregular aggregates of black organic matter, abundant shell fragments, some Fe staining. Colour: dark yellowish-brown 10YR 4/6
2	- 30	WRFWB (? bed d)	Fine sands and coarse silts, moderate-sorting of matrix , mm-scale laminae, some pebbles, some Fe staining. Colour: yellow, 10YR 7/6

*Sample 14 was sampled ~20 m west of the main section. Here the upper part of bed f is fossiliferous and less altered than the upper part near the Elephant excavation, suggesting that the oxidised Fe bed thins and thickens laterally.

WRFWB samples, incomplete removal of organic matter and $CaCO_3$ contents treated in this way caused problems in orientating clay minerals during smear slide preparation (see below). To improve this the WRFWB samples were leached with 10% HCl to further remove $CaCO_3$ and combusted at 250°C in a muffle furnace to burn off refractory organic matter. The <2 µm fraction of each sample was isolated by pipette analysis and the resulting clay fraction was magnesium (Mg^{2+}) saturated in 1 molar $MgCl_2$ solution to sharpen diffractogram peaks. The clay preparation was then smeared onto glass slides to orientate clay platelets such that diagnostic basal reflections were clear.

Clay minerals were identified on the basis of their air dried, glycolated and heat treated diffraction peak positions after Biscaye (1965). Semi quantitative analysis of clay mineral abundances using peak areas (Biscaye 1965) was possible for samples 2, 5, 9, 10, 13, 14 and 15 (Table 3), where peak definition was clear enough to allow peak area comparisons. For other samples where peak resolution was poor the clay mineral types and relative peak areas were noted but not quantified.

To help identify the source of smectite clays, an aliquot of each <2 µm fraction was potassium (K^+) saturated by placing it in 1N KOH for 15 hours, followed by boiling for 1 hour (Weaver 1958). The response of smectite clays to this treatment is broadly indicative of the parent material from which the clay derived. Smectites resulting from argillisation of sheet silicates suffer complete collapse of the smectite to a 10 Å 'illitic' position. Conversely, smectite derived from volcanogenic material inherits a lower charge from the parent material, such that expandable layers only partially collapse, marked by an incomplete peak migration toward 10 Å (Walkden 1972).

Two samples in the lower and upper parts of the WRFWB (3 and 7) were also used for <63 µm particle size analysis. Thirty grams of bulk sample was mixed in a dispersing solution (2.55 g l^{-1} sodium hexametaphosphate), and passed through a 63 µm sieve to separate the <63 µm fraction. The <63 µm fraction was then separated by pipette analysis (Folk 1980) and the dry weights of each fraction used to calculate the percentages of each size fraction.

RESULTS

The results of the grain-size analysis show that 22-28(±0.01)% of the grains are medium silt to clay-sized (Table 2) and that between 5 and 7% of the particles represent the <2 µm clay fraction: using Folk (1980) the WRFWB sediments classify as 'slightly gravelly muddy sands.'

Table 2. Grain size data for samples 3 and 7, WRFWB

	Sample 3		**Sample 7**	
Grain size (µm)	**Grain size distribution %**	**Cumulative percentage**	**Grain size distribution %**	**Cumulative percentage**
>63	40.3	40.3	18.7	18.7
62.5	17.4	57.7	24.2	42.9
31	10.6	68.3	16.5	59.4
15.6	10.6	78.9	14.0	73.4
7.8	6.6	85.5	11.4	84.8
3.9	7.9	93.4	10.2	95.0
2	6.6	100.0	5.0	100.0
TOTAL	100.0	100.0	100.0	100.0

Table 3. Semi quantitative clay mineral percentages for the seven samples with high quality peak resolution.

Sample	**% kaolinite**	**% Illite**	**% smectite**
Sample 15 Modern salt marsh (Stiffkey)	18	47	35
Sample 13 Runton Till	9	61	30*
Sample 10 Mundesley Member	7	38	55
Sample 9 WRFWB (oxidised Fe bed)	10	0	90
Sample 14 WRFWB (bed f)	9	43	48
Sample 5 WRFWB (bed f)	8	31	61
Sample 2 WRFWB (bed d)	9	61	30*

*illite/smectite mixed layer clay

Typical diffractograms are shown in Figure 3. Relative to all the other samples in this study, diffraction patterns from the main part of the WRFWB had suppressed basal reflections and a reinforced secondary reflection at 3.5-4 Å. We suspect that these features result from poorly orientated clay platelets caused mainly by incomplete removal of organic matter, despite the more aggressive preparation techniques described above. Although these problems caused weak XRD responses, the peak positions were still clear and unambiguous, such that mineralogical identification was possible. Moreover, suppressed basal reflections were not a feature of samples from the upper 15-20 cm of the WRFWB, 'the oxidised Fe bed'. Indeed samples from the oxidised Fe bed, showed a very clear 14 Å smectitic peak.

Clay suites

The samples in this study all contained a 14 Å smectite peak, a 10 Å illite peak and a 7Å kaolinite peak (Fig. 3.) We found no evidence of the vermiculite (weathered smectite) reported by Hannam *et al.*, (1996). In the samples where clay mineral percentages were resolved (Table 3) the following features are clear. 1) Kaolinite is the least common clay type (typically <10% abundance). 2) Illite typically represents 38-66% of the clay mineral assemblage. 3) Smectite is present in all samples, either interstratified with illite (samples 2 and 13) or as a discrete mineral typically between 25-90% abundance. 4) Smectite is most abundant (47-90%) in samples from the WRFWB (samples 5, 9 and 14) and in the clays in the basal Mundesley Member (sample 10).

DISCUSSION

The clay mineralogy data show that typical detrital sedimentary units (e.g. sample 13; Runton Till (Fig. 3a) and sample 15 modern Stiffkey saltmarsh) contain a mixture of illite, smectite and kaolinitic clay: however, the smectite component is not greater than 35%, and typically it shows mixed-layer characteristics with illite (Fig. 3a). Samples from the wider Cromer Forest-bed Formation show similar characteristics to these detrital clay suites, and overall they are comparable to inherited clay suites from Holocene sediments in the Wash-Fenland embayment (Brew *et al.*, 2000). By contrast the WRFWB samples contain higher percentages of smectite clay (Fig. 3b): although we were not able to quantify the amount of smectite present below sample 5 (see above), it is our general impression that XRD patterns from the lower part have smectite contents comparable to that of sample 5 (i.e. ~60%). This suggests quite abundant smectite in the WRFWB bed as a whole, although with increased concentrations toward the upper part (see below). Sample 10 (Fig. 3c) from marine tidal sand units of the Mundesley Member, from the base of a bed directly overlying the basal 'Monkey Gravel', and 20 cm above the WRFWB also contained >50% smectite.

Most strikingly, smectite is the dominant clay mineral in the oxidized Fe bed of the WRFWB (sample 9; Fig. 3d) whereas illite is either not present, or at such low concentrations that it is totally masked by the large smectite peak. Since it is clear that the oxidised Fe bed has suffered post-depositional oxidation and leaching (Hannam *et al.*, 1996; Bottrell *et al.*, 1998) it is possible this alteration has also caused the distinctive clay mineralogy. Alteration of detrital illites and slow removal of base cations, particularly in the presence of Mg^{2+}, could explain smectite formation at the expense of illite (Brady and Weil 2002), a scenario consistent with the organic carbon and sulphide early diagenesis (Hannam *et al.*, 1996; Bottrell *et al.*, 1998). Smectite is, however, also abundant in the basal Mundesley Member clay units, just 20 cm above

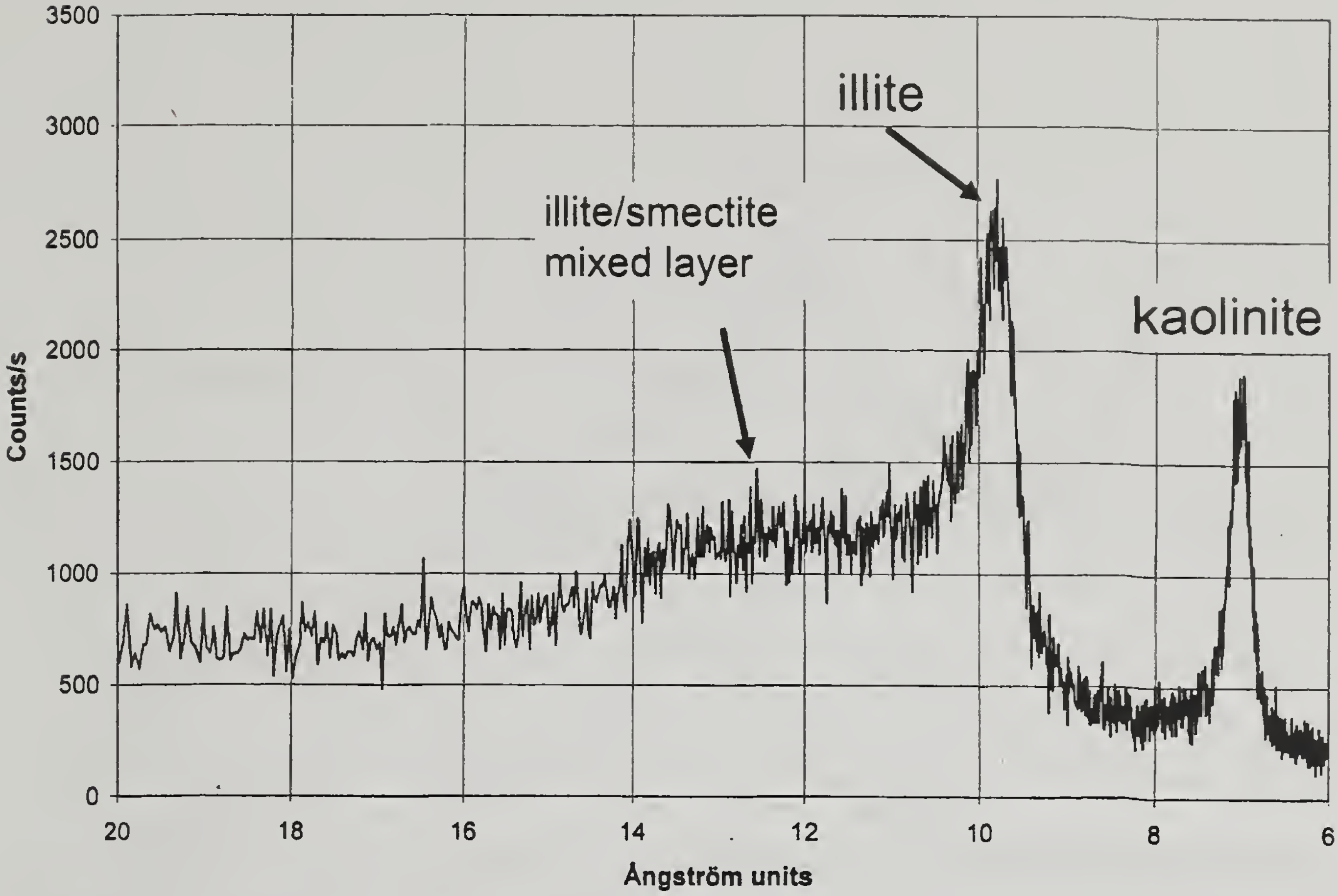


Fig. 3a. Air dried X-ray diffraction trace for sample 13 Runton Till dominated by 10 Å illite peak and 7 Å kaolinite peak , with some interstratified illite/smectite (11-14 Å).

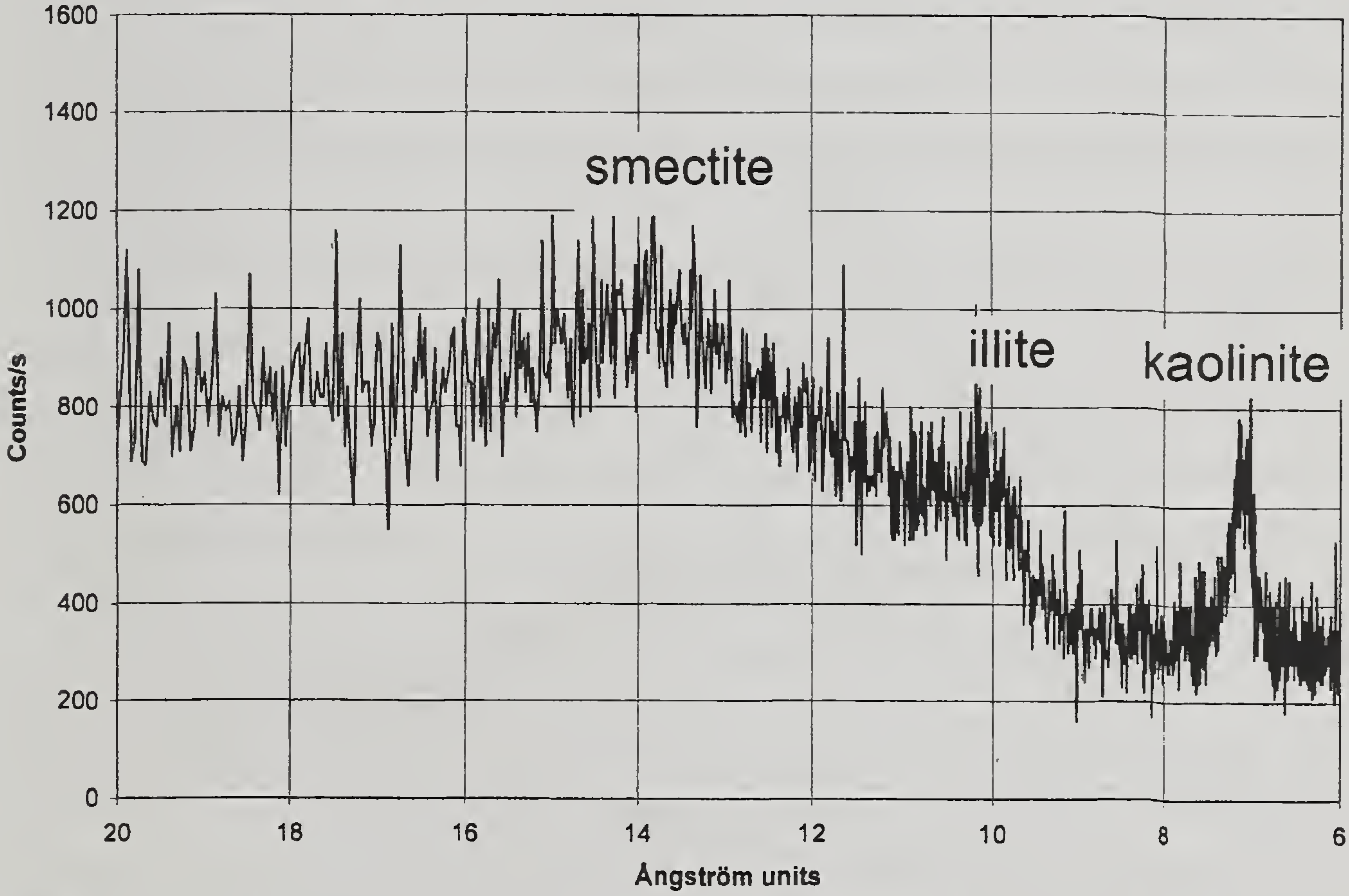


Fig. 3b. Air dried X-ray diffraction trace for sample 14, upper WRFWB showing broad 14 Å smectite peak (possibly with some illite interstratification), a 10 Å illite peak and 7 Å kaolinite peak. The 'hairy' appearance of the trace is caused by high organic matter content and poor orientation of clay platelets.

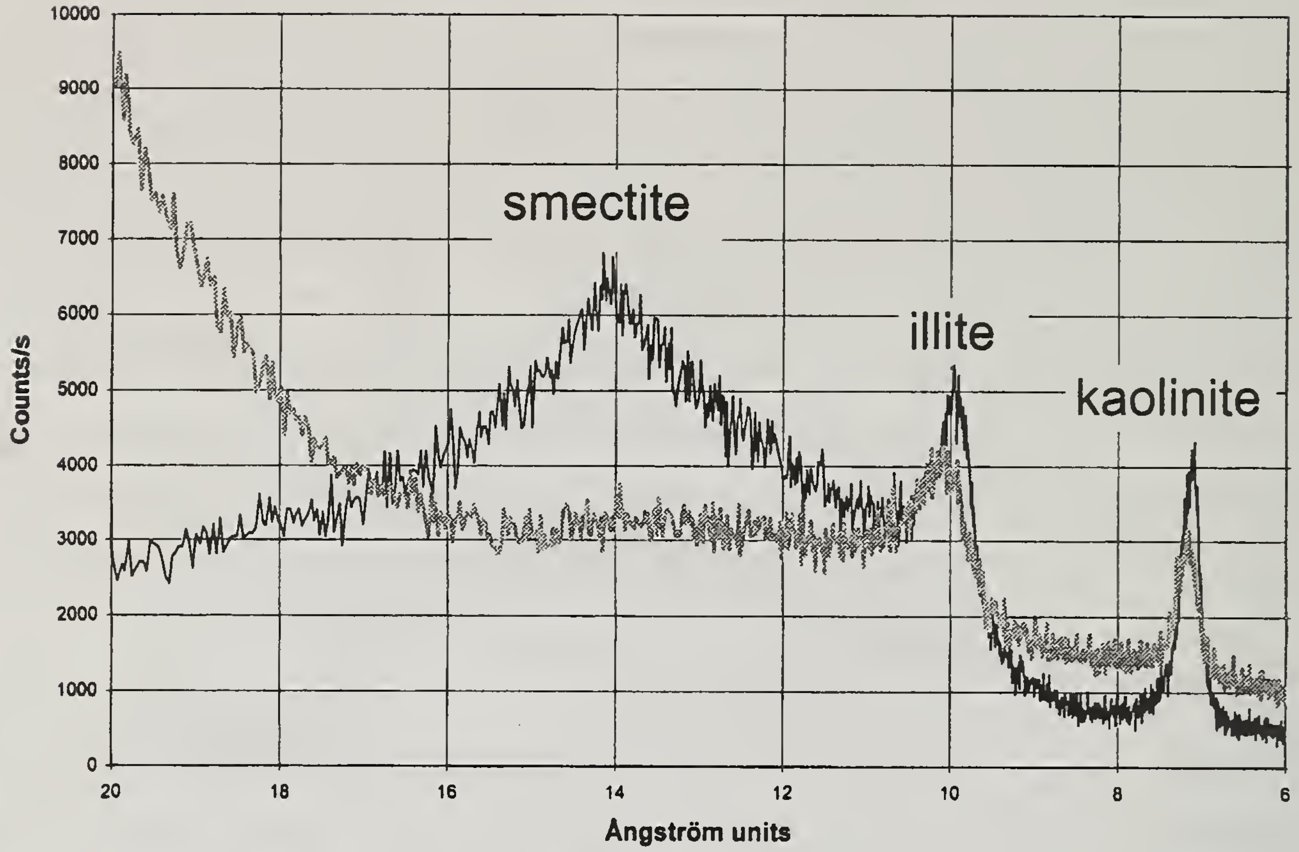


Fig. 3c. Air dried (black) and K^+ saturated (grey) X-ray diffraction traces for sample 10, basal Mundesley Member above 'Monkey Gravel' showing clear 14 Å smectite peak, a 10 Å illite peak and 7 Å kaolinite peak. The 14 Å peak collapses completely after K^+ saturation indicating a detrital or soil clay smectite.

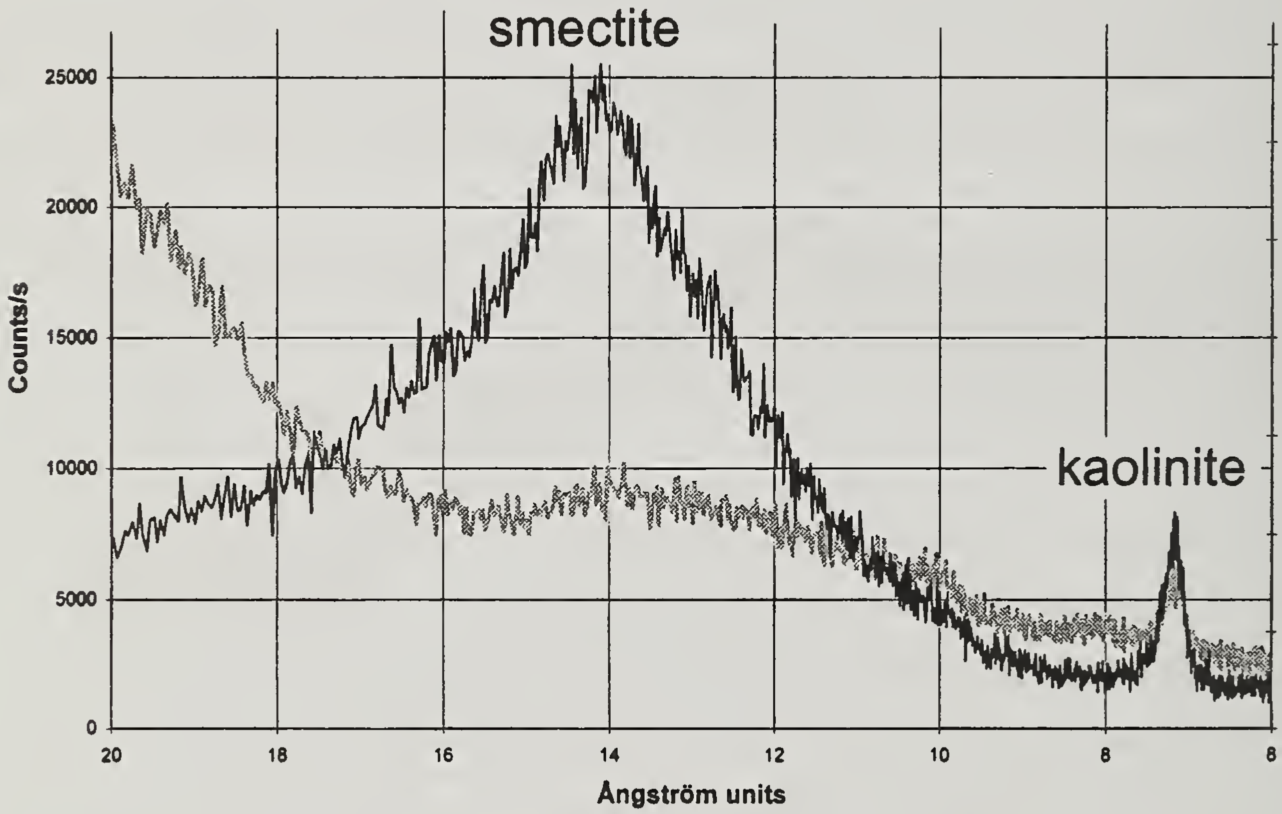


Fig. 3d. Air dried (black) and K^+ saturated (grey) X-ray diffraction traces for sample 9, WRFWB oxidized Fe bed showing dominant 14 Å smectite peak, and 7 Å kaolinite peak. The 14 Å peak mostly collapses after K^+ saturation; a 10 Å illite peak is not well-developed after this treatment, which may indicate a partial volcanogenic source for the smectite .

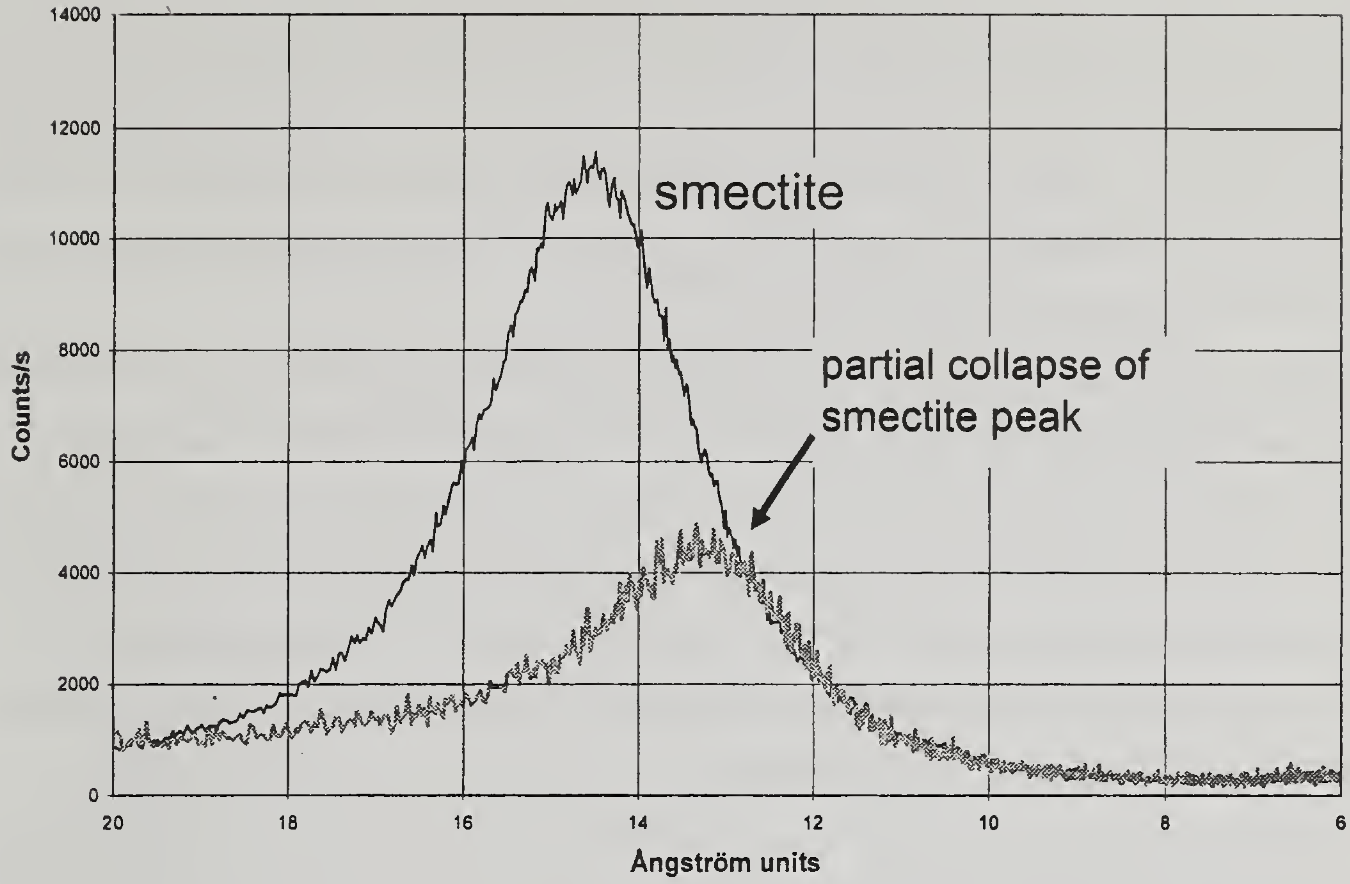


Fig. 3e. Air dried (black) and K^+ saturated (grey) X-ray diffraction traces for sample 16, the bentonite clay 'standard' showing 14 Å smectite peak that partially collapses and migrates to lower angles after K^+ saturation. Note that a 10 Å illite peak is not well developed after K^+ saturation.

the top of the WRFWB where there is no evidence of extensive post-depositional alteration: indeed the preservation of aragonitic *Mya truncata*, in the 20 cm of muddy gravels that separate sample 9 (oxidized Fe bed, WRFWB) and sample 10, argue strongly against groundwater leaching above the WRFWB.

We conclude that >50% smectite content is either an original feature of the WRFWB, or a result of early diagenetic smectite formation in the sediment: its response to K^+ saturation is thus important to help infer its origin (see above). The bentonite 'standard' clay (sample 16; Fig. 3e) showed only partial peak collapse and migration of about 2Å toward higher angles from its starting position; a 10 Å illite peak is not developed, results that are consistent with those of Weaver (1958) for volcanogenic smectites. However, samples 3, 5 and 6 from the lower part of the WRFWB, and sample 10 (Fig. 3c) from the basal part of the Mundesley Member showed essentially complete collapse of the 14 Å smectite peak towards a 10 Å illite peak, more consistent with the response of non-volcanogenic detrital or early diagenetic clays. The exception was sample 9, from the oxidised Fe bed (Fig. 3d), which showed a response more similar to the bentonite standard: here collapse was quite significant, similar to that figured by Hannam *et al.*, (1996), although a clear 10 Å illite peak did not develop. The control sample (16) from Stiffkey Marsh rather surprisingly showed little response to K^+ saturation, with almost no collapse or migration. These results mostly do not support a dominant volcanogenic source for the smectite clays, excepting the sample from the oxidised Fe bed, which shows some of the characteristics expected of volcanogenic clays.

Taken overall these findings suggest that smectite clays in the Cromer Forest-bed Formation sediments are generally either detritally sourced, or formed by early diagenetic alteration of illites in marshy waterlogged conditions (see also Hannam *et al.*, 1996), rather than from alteration of volcanic dust. Greater than 50% smectite concentrations *throughout* the bed are consistent with this interpretation and the overall mass of smectite is small, typically <3% of the bulk sediment. We also stress that, excepting sample 9, the smectite response to K^+ saturation is not strongly diagnostic of volcanogenic sources.

Greater than 55% smectite clays in the basal Mundesley Member sediments might simply result from the re-working of smectitic clays from the upper WRFWB itself. This observation might support the suggestion that the top of the WRFWB had been truncated by erosion before deposition of the overlying marine sequence (Preece & Parfitt 2000), and also indicate that diagenetic smectite formed in the WRFWB very soon after sedimentation.

VOLCANOGENIC SOURCES TO WRFWB?

Although the results of this study largely do not support the presence of volcanogenic smectites in the WRFWB, we do note that a volcanic mineral assemblage has recently been described from the 20-120 μm size fraction of the WRFWB (Brough *et al.*, in press). These authors have shown that glass shards are extremely rare but are present mainly at the equivalent horizon of sample 3 (this study; Table 1). This micro-tephra assemblage is indicative of a potassic mineral suite, possibly from an evolved phonolitic or trachytic melt. Mineralogical and electron microprobe data are inconsistent with a tephra source from mid Atlantic ridge sites and the amphibole and alkali feldspar components are more evolved than early Quaternary mineral assemblages from West Eifel volcanism in Germany. The mineral assemblage and geochemical compositions are most similar to those from the Mont Dore area (Massif Central, France) and the Italian volcanic complex of Mount Vulture in the southern Apennines. With this additional evidence it would not be surprising that a small amount of the smectites in the WRFWB is sourced from the alteration of volcanic dust.

ACKNOWLEDGEMENTS

We thank Emma Knight and Angela Byrne (UEA) for help in the laboratory: Stephen Bennett (UEA) ran the X-ray diffractometer and helped with XRD data processing.

REFERENCES

ANDREWS, J.E., BRIMBLECOMBE, P., JICKELLS, T.D., LISS, P.S. & REID, B. 2004. *An Introduction to Environmental Chemistry*, 2nd Edition. Blackwell Publishing, Oxford, 296 pp.

BANHAM, P.H. 1968. A preliminary note on the Pleistocene stratigraphy of north-east Norfolk. *Proceedings of the Geologists' Association*, **79**, 469-474.

BISCAYE, P. E. 1965. Mineralogy and sedimentation of recent deep sea clay in the Atlantic Ocean and adjacent seas and oceans. *Geological Society of America Bulletin,* **76**, 803-832.

BOTTRELL, S.H., HANNAM, J.A., ANDREWS, J.E., & MAHER, B.A. 1998. Diagenesis and remobilization of carbon and sulphur in Mid-Pleistocene organic-rich freshwater sediment. *Journal of Sedimentary Research,* **68**, 37-42.

BRADY, N.C. & WEIL, R. R. 2002. *The Nature and Properties of Soils*. 13th Ed. Prentice Hall, New Jersey, 960 pp.

BREW, D.S., HOLT, T., PYE, K. & NEWSHAM, R. 2000. Holocene sedimentary evolution and palaeocoastlines of the Fenland embayment, eastern England. In: Shennan, I. and Andrews, J.E. (eds). *Holocene Land-Ocean Interaction and Environmental Change around the North Sea*. Geological Society, London, Special Publication **166**: The Geological Society, London, pp. 253-257.

BROUGH, S., BARCLAY, J., ANDREWS, J.E., & BESCOBY, D. in press. Micro-tephra in the West Runton Freshwater Bed: preliminary results. *Quaternary International*.

FOLK, R.L. 1980. Petrology of sedimentary rocks. Hemphill Publishing, Austin, 179 pp.

GIBBARD, P.L., BOREHAM, S., ANDREWS, J.E., MAHER, B.A. in press. Sedimentation, geochemistry and palaeomagnetism of the West Runton Freshwater Bed, Norfolk, England. *Quaternary International*.

HANNAM, J. A., ANDREWS, J. E. & Bottrell, S. H. 1996. Carbon and sulphur geochemistry and clay mineralogy of the West Runton Freshwater Bed. *Bulletin of the Geological Society of Norfolk*, **45**, 29-51.

LEE, J.R., BOOTH, S.J., HAMBLIN, R.J.O., JARROW, A.M., KESSLER, H., MOORLOCK, B.S.P., MORIGI, A.N., PALMER, A., PAWLEY, S.J., RIDING, J.B. & ROSE, J. 2004. A new stratigraphy for the glacial deposits around Lowestoft, Great Yarmouth, North Walsham and Cromer, East Anglia. *Bulletin of the Geological Society of Norfolk*, **53**, 3-60.

PREECE, R.C. & PARFITT, S.A. 2000. The Cromer Forest-bed Formation: new thoughts on an old problem. In: Lewis, S.G., Whiteman, C.A. and Preece, R.C. (eds), *The Quaternary of Norfolk and Suffolk, Field Guide*, Quaternary Research Association, London, pp.1-28.

STUART, A.J. 1975. The vertebrate fauna of the type Cromerian. *Boreas*, **4**, 63-76.

STUART, A. J. 1991. An Elephant skeleton from the West Runton Freshwater Bed. *Bulletin of the Geological Society of Norfolk*, **41**, 75-90.

WALKDEN, G. M. 1972. The mineralogy and origin of interbedded clay wayboards in the Lower Carboniferous of the Derbyshire Dome. *Geological Journal,* **8**, 143-160.

WEAVER, C.E. 1958. The effects and geologic significance of potassium fixation by expandable clay minerals derived from muscovite, biotite, chlorite and volcanic material. *American Mineralogist,* **43**, 839-861.

WEAVER, C.E. 1989. *Clays, Muds and Shales*. Developments in Sedimentology 44, Elsevier, Oxford, 820 pp.

WEST, R.G. 1980. *The Pre-glacial Pleistocene of the Norfolk and Suffolk Coasts*. Cambridge University Press, Cambridge, 203 pp.

[Manuscript received 25 October 2007; revision accepted 30 November 2007]

CONTENTS

Page

Editorial 1

Leeder, M.R.
Tectonics, surface uplift and river incision: general models, case histories and applications to East Anglia and southern England. 3

Hoare, P.G. and Larkin, N.R.
The glacial erratic collection at Norwich Castle Museum. 37

Brough, S. and Andrews, J.E.
Clay mineralogy of Cromer Forest bed Formation sediments, West Runton, Norfolk. 63

The Geological Society of Norfolk exists to promote the study and understanding of geology in East Anglia, and holds meetings throughout the year. For further details consult our Web Site (http://www.norfolkgeology.co.uk) or write to The Secretary, Geological Society of Norfolk, 32, Lenthall Close, Norwich, NR7 0UU.

Copies of the Bulletin (including older back copies) can be obtained from the editor at the address on p.1; it is issued free to members.

The figure on the front cover is Figure 7 from the paper by Hoare and Larkin in this issue of the Bulletin, showing a beautifully preserved specimen of *Neuropteris gigantea* Sternberg, an Upper Carboniferous seed fern fossil found inside an erratic clast in Carbrooke pit, near Watton, Norfolk,

ISSN0143-9286